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Mechanisms proposed through experimental investigations on thermophysical properties and forced convective heat transfer characteristics of various nanofluids – A review

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ABSTRACT

Experimental investigations on thermophysical properties and forced convective heat transfer characteristics of various nanofluids are reviewed and the mechanisms proposed for the alteration in their values or characteristics due to the addition of nanoparticles are summarized in this review. A comprehensive review on the experimental works on specific application of nanofluids is also presented. As the literature in this area is spread over a span of two decades, this review could be useful for researchers to have an accurate screening of wide range of experimental investigations on thermophysical properties, forced convective heat transfer characteristics, the mechanisms involved and applications of various nanofluids.

Contents

1. Introduction

Nanofluids are advanced and functionalized fluids that are designed by adding nanosized solid particles in low to moderate volumetric fractions to a base fluid. Nanofluids provide the following advantages: (i) nanosized particles have enhanced stability against sedimentation since surface forces easily balance the gravity force, and (ii) thermal, optical, mechanical, electrical, rheological, and magnetic properties of nanoparticles, which depend significantly on size and shape, can be customized during manufacture. Hence, nanofluids are often superior to base fluid.

Masuda et al. [1] were the first to conduct experiment to show that there was alteration in the values of thermal conductivity and viscosity of liquids containing dispersed ultra fine particles of 13 nm size. However, the concept of nanofluids was first materialized by Choi [2] after performing a series of research works at Argonne National Laboratory of USA. Subsequent researches [3–5] have showed that the nanofluids exhibited higher thermal conductivity even for low concentration of suspended nanoparticles.

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These enhanced thermal properties are not merely of academic interest. These exciting results on nanofluid thermal conductivity make nanofluids promising for applications in thermal management systems. Nanofluids have several other potential benefits like improved heat transfer and reduced pumping power, miniaturized (smaller and lighter) heat exchangers with reduced heat transfer fluid inventory and reduced emissions, and suitable for applications in micro channel flow passages. Recent experiments have also demonstrated that nanofluids have attractive properties for applications in the area of heat transfer, drag reduction, binding ability for sand consolidation, gel formation, wettability alteration, and corrosive control. The tribological performance of lubricating oils can also be significantly improved by dispersing carbon and metallic-based nanoparticles in these lubricants. A reduction of the friction coefficient by over 25% is expected with nickel-based nanoparticles added to lubricants.

Tzeng et al. [6] experimentally studied the effect of adding CuO and Al_2O_3 nanoparticles and antifoam respectively into cooling engine oil using a real-time four-wheel-drive transmission system. The transmission system adopts an advanced rotary blade coupling, where a high local temperature occurs easily at high rotating speed. Therefore, it is imperative to improve the heat transfer efficiency. A comparison is made between the heat transfer performance of cooling oil with and without adding such substances. The experimental results revealed that oil containing CuO nanoparticle has the lowest temperature distribution both at high and low rotating speed and accordingly the best heat transfer effect. Antifoam has the highest temperature distribution in the same conditions and hence the worst heat transfer effect.

Nguyen et al. [7] have experimentally investigated the heat transfer enhancement of an Al_2O_3/water nanofluid flowing inside a closed system that is destined for cooling of microprocessors or other electronic components. Experimental data were obtained for turbulent flow regime and it was clearly shown that the inclusion of nanoparticles into distilled water produced a considerable enhancement of the cooling block convective heat transfer coefficient.

Jaekeun et al. [8] investigated the tribological properties of fullerene nanoparticles added mineral oil as a function of volume concentration of fullerene nanoparticle additives. The authors reported that the nano-oil containing higher volume concentration of fullerene nanoparticles resulted in the lower friction coefficient and less wear, indicating that the increase of fullerene nanoparticle additives improved the lubrication properties of regular mineral oil. Improved lubrication properties was attributed to the facts like (i) the added fullerene molecules may accelerate self-restoration of the polymeric tribofilm damaged in the course of mechano chemical degradation and (ii) the fullerene particles with a spherical structure play a role of ball bearing in the friction surfaces.

Superior high temperature drilling fluids was also engineered through the use of nanofluids by Tran and Lyons [9] to meet the increasingly demanding conditions of high temperature and pressure found in some deep wells. The benefits of using drag-reducing polymer additives with nanoparticles to improve the drilling penetration rate, cleaning, lubrication, and cooling for the drill bit were quantified. Thus, they established that nanofluids will significantly improve drilling speed and eliminate damage to the reservoir rock.

As heat transfer enhancement in solar devices is one of the key issues of energy saving and compact designs, Natarajan and Sathish [10] analyzed and compared the heat transfer properties of the nanofluids with the conventional fluids. They concluded that thermal conductivity enhancement depends on the volume fraction of the suspended particles and thermal conductivities of the particles and base fluids. Their experiment proved that the nanofluid is more effective than the conventional fluids and if these fluids are used as a heat transport medium, it increases the efficiency of the traditional solar water heater.

In electric transformers, thermally driven failures due to instantaneous overload are common. This is due to relatively low thermal conductivity of transformer oil. Therefore, if the thermal conductivity of the transformer oil is increased, considerable extension in transformer lifetime and increment in load/cooling capacity may be achieved. Hence ceramic nanoparticles are chosen for study by Choi et al. [11] to make high efficiency transformer oil because they have an electric insulation property.

Shen et al. [12] investigated the wheel wear and tribological characteristics in wet, dry, and minimum quantity lubrication (MQL) grinding of cast iron. Water-based Al_2O_3 and diamond nanofluids were applied in the MQL grinding process and the grinding results were compared with those of pure water. Experimental results showed that G-ratio, defined as the volume of material removed per unit volume of grinding wheel wear, could be improved with high-concentration nanofluids. Nanofluids showed the benefits of reduced grinding forces, improved surface roughness, reduction in grinding temperature and prevention of work piece burning.

In Michelin North America tire plants, the productivity is limited by the ability to efficiently cool the rubber as it is being processed. This necessitates the use of over 2 million gallons of heat transfer fluids for Michelin's U.S. plants. Michelin hopes to realize a 10% productivity increase in its rubber processing plants if viable water-based nanofluids can be developed and commercially produced in a cost-effective manner. The successful demonstration of nanofluids at Michelin's plant will open doors for the use of nanofluids in other industries and applications that require efficient thermal management. Examples are public utilities; oil and gas industry; food and beverage processing industry; chemicals and plastics industry; solar energy conversion to electricity; and heating, ventilation, and air conditioning (HVAC) systems for buildings [13].

During annealing, the steel takes a long time, as much as 16 h, to cool. The steel strips are cooled by a flow of hydrogen gas, which in turn is cooled in a heat exchanger where flowing water cools the gas before it re-enters the steel chamber. This cooling stage is a bottleneck area and a more efficient coolant is required to cut down the time taken to cool the steel and increase the overall productivity of the unit. This was the area where a team of members from Tata Steel, India decided to employ the nanofluid technology with an attempt to bring down cooling time by as much as 1–2 h per cycle. A 1-h reduction in cycle time translates into additional revenue of over $1 million every year with increased annealed steel production [14].

Kulkarni et al. [15] evaluated the performance of nanofluids for the application of heating buildings in cold regions. They performed calculations for conventional finned-tube heat exchangers used in buildings in cold regions. The analysis showed that using nanofluids in heat exchangers could reduce volumetric and mass flow rates, and result in an overall pumping power savings. Nanofluids necessitate smaller heating systems, which are capable of delivering the same amount of thermal energy as larger heating systems using base fluids, but are less expensive; this lowers the initial equipment cost excluding nanofluid cost. This will also reduce environmental pollutants because smaller heating units use less power, and the heat transfer unit has less liquid and material waste to discard at the end of its life cycle. They also have indicated that similar benefits can be derived by considering nanofluids in place of chilled water in building cooling coils.

Kim et al. [16] acquired experimentally the quenching curves for small metallic spheres exposed to pure water and water-based nanofluids with alumina, silica and diamond nanoparticles at low concentrations. The results show that the quenching behavior in

nanofluids is nearly identical to that in pure water. However, it was found that some nanoparticles accumulate on the sphere surface, which results in destabilization of the vapor film in subsequent tests with the same sphere, thus greatly accelerating the quenching process. It was revealed that alumina and silica nanoparticle deposition on the surface increases the critical heat flux and minimum heat flux temperature, while diamond nanoparticle deposition has a minimal effect on the boiling curve. The possible mechanisms by which the nanoparticles affect the quenching process was attributed to the surface roughness increase and wettability enhancement due to nanoparticle deposition for the premature disruption of film boiling and the acceleration of quenching.

Buongiorno et al. [17] demonstrated that the nanofluids could be used to enhance the in-vessel retention (IVR) capability in the severe accident management strategy implemented by certain light-water reactors. It is envisioned that, at normal operating conditions, the nanofluid would be stored in dedicated storage tanks, which, upon actuation, would discharge into the reactor cavity through injection lines. The design of the injection system was explored with risk-informed analyses and computational fluid dynamics. It was determined that the system has a reasonably low failure probability and the nanofluid once injected would be delivered effectively to the reactor vessel surface within seconds. It was also shown analytically that the increase in decay power removal through the vessel using a nanofluid is about 40%, which could be exploited to provide a higher IVR safety margin or to enable IVR at higher core power for a given margin. In general, nanofluids could enhance economics and safety of nuclear reactors. They also have great potential as a coolant for safer and smaller nuclear generators in the future [18].

Chang et al. [19] investigated the tribological behavior of the lubricant with TiO_2 nanoparticles on the surface of piston ring is compared with that of the lubricant without TiO_2 nanoparticles. The coefficients of friction of base lubricant and TiO_2 nanolubricant were 0.15 and 0.14, respectively. In addition, as observed from the measured result of wear rate, when using TiO_2 nanolubricant as the lubricant, the wear amount of piston ring was less than that of base lubricant. Therefore, it was concluded that the base lubricant with TiO_2 nanoparticles has better tribological efficiency than general base lubricants.

Kole and Dey [20] have presented experimental results on the viscosity of the nanofluids prepared by dispersing alumina nanoparticles in commercial car coolant. They revealed that the pure base fluid display Newtonian behavior over the measured temperature, while it transforms to a non-Newtonian fluid with addition of a small amount of alumina nanoparticles. Their results show that viscosity of the nanofluid increases with increasing nanoparticle concentration and decreases with increase in temperature. They showed that while most of the frequently used classical models severely under predicted the measured viscosity while it could be predicted fairly well by theoretical model taking into account the effect of Brownian motion of nanoparticles in the nanofluids.

Leong et al. [21] studied the application of ethylene glycol based copper nanofluids in an automotive cooling system. It was observed that, overall heat transfer coefficient and heat transfer rate in engine cooling system increased with the usage of nanofluids compared to ethylene glycol (i.e. base fluid) alone. It is observed that about 3.8% of heat transfer enhancement could be achieved and also estimated that the air frontal area could be reduced by 18.7% with the addition of 2% copper particles in a base fluid.

Suleimanov et al. [22] presented an experimental study of nanofluids intended for enhanced oil recovery. It was demonstrated that production rate of oil displaced by the nanofluid is increased by 1.5 fold in comparison with the aqueous solution of anionic surface-acting agent and 4.7 fold in comparison with water. In homogeneous porous medium, the oil recovery with nanofluid increased to 51% and 35% respectively when compared with that of water and surfactant solution. In heterogeneous porous medium, the oil recovery with nanofluid increased to 66% compared with water.

Table 1 summarizes the research works that demonstrated the application of nanofluids as coolants/working fluid in the existing systems. This indicates that there is an excitement being created in the research community about using nanofluids to meet new challenges in cooling and thermal management of high heat flux devices. It is also believed that there are more than 300 research groups and companies worldwide who are involved with nanofluids research [23]. Thus nanofluids have received great attention for past two decades which has resulted in an exponential growth of annual research publications on nanofluids. Even a text book entirely dedicated to nanofluids has been released by Das et al. [24] and many reviews articles on nanofluid research has been published for almost every year in the recent past. The summary of the previous reviews [25–48] on nanofluid research is given in Table 2. These reviews have provided discussions on following aspects of nanofluids like

- Synthesis of nanoparticles.
- Preparation and stability.
- Potential applications.
- Theoretical and experimental investigations of thermophysical properties.
- Experimental techniques for thermal conductivity measurements.
- Mechanisms for enhanced thermal conductivity.
- Experimental and analytical investigations of convective and boiling heat transfer.
- Nanofluid heat transfer and pressure drop correlations.
- Heat transfer performance of different nanorefrigerants.
- Thermal conductivity of carbon nanotube (CNT).

From the literature review it is learnt that despite recent advances in nanofluid technology such as discoveries of unexpected thermal properties, new mechanisms and unconventional models proposed, there are a number of issues which have not been fully investigated and the mysteries of nanofluids are unsolved. For example, the results of the proposed theoretical models or correlations for calculating nanofluid thermophysical properties and heat transfer characteristics seem to agree with experimental data of a certain group of authors is found to disagree with data of other authors. It is also understood that due to large level of scatter and inconsistency in the published data, the development of a comprehensive model which can explain all the trends has become a difficult task. Hence in this review, literature based on experimental works on thermophysical properties and forced heat transfer characteristics with the mechanisms proposed for the alteration in their values is summarized.

2. Thermophysical properties of nanofluids

2.1. Thermal conductivity of nanofluids

Anomalous enhancement observed in thermal conductivity of nanofluids has made nanofluid a prospective coolant for many applications and has been received considerable attention by the researchers. The effective thermal conductivities of Al_2O_3/water nanofluids with low volume concentrations from 0.01% to 0.3% were measured by Lee et al. [49]. The measured thermal conductivities of the dilute Al_2O_3/water nanofluids increase nearly linearly with volume concentration and a maximum enhancement of 1.44%

Table 1
Summary of previous research works on the demonstration of the application of nanofluids as coolants/working fluid in the existing systems.

Application	Researcher	Nanofluid	Influencing property of nanofluid
Automobile transmission	Tzeng et al. [6]	CuO, Al_2O_3, antifoam/engine oil	Improved heat transfer efficiency
Electronics cooling	Nguyen et al. [7]	Al_2O_3/water	Increased heat transfer coefficient
Tribology	Jaekeun et al. [8]	Fullerene nanoparticles/mineral oil	Nanoparticle helps in self-restoration of the damaged polymeric tribofilm and play a role of ball bearing in the friction surfaces
Drilling fluids	Tran and Lyons [9]	[a]	Improved drilling penetration rate, cleaning, lubrication, and cooling
Solar water heater	Natarajan and Sathish [10]	CNT/distilled water	Enhanced thermal conductivity
Electric transformers	Choi et al. [11]	Al_2O_3/transformer oil	Enhanced thermal conductivity
Grinding	Shen et al. [12]	Al_2O_3, diamond/water	Benefits of reducing grinding forces, improving surface roughness, and preventing work piece burning
Rubber processing	Routbort [13]	Water-based nanofluids	Efficient coolant
Annealing	Matthew [14]	[a]	Efficient coolant
Heating of buildings (HVAC)	Kulkarni et al. [15]	CuO, Al_2O_3, SiO_2/EG and water mixture	Higher heat transfer coefficient
Quenching	Kim et al. [16]	Alumina, silica, diamond/water	Surface roughness increase and wettability enhancement due to nanoparticle deposition
Nuclear reactor	Buongiorno et al. [17,18]	Al_2O_3/water	CHF enhancement
Tribology	Chang et al. [19]	TiO_2/automotive lubricant	Nanoparticles were inlaid in the ditch of piston ring formed by wear and enhancing the lubrication effect
Automobile cooling	Kole and Dey [20]	Al_2O_3/commercial car engine coolent	Viscosity effects were investigated
Automotive car radiator	Leong et al. [21]	Cu/ethylene glycol	Improved heat transfer rate
Oil recovery (Oil & Gas Industries)	Suleimanov et al. [22]	Non-ferrous metal/water	Decrease of interfacial tension on the nanofluid–oil interface and improvement of pore wettability cause an energy reduction of oil because of which the oil flow rate is increased

[a] Not mentioned.

Table 2
Summary of the previous reviews on nanofluid research.

Researcher	Aspects reviewed
Keblinski et al. [25]	Synthesis, thermal conductivity, boiling and convective heat transfer
Das et al. [26]	Synthesis, thermal conductivity, convection and boiling heat transfer, applications
Wang and Mujumdar [27]	Thermal conductivity, viscosity, free and forced convection transfer, boiling heat transfer
Trisaksri and Wongwises [28]	Experimental and analytical investigations on thermal conductivity of nanofluids, boiling heat transfer and convective heat transfer
Daungthongsuk and Wongwises [29]	Experimental and numerical investigation the forced convective heat transfer of the nanofluids
Murshed et al. [30]	Synthesis, potential applications, experimental and analytical studies on the effective thermal conductivity, effective thermal diffusivity, convective heat transfer, and electrokinetic properties are critically reviewed
Yu et al. [31]	Pertinent parameters of particle volume concentration, particle material, particle size, particle shape, base fluid material, temperature, additive, and acidity were considered individually, and experimental results from multiple research groups were assessed
Taylor and Phelan [32]	Nanofluid pool boiling
Choi [33]	Highlights recent advances in the field of nanofluids research and shows future directions in nanofluids research through which the vision of nanofluids can be turned into reality
Li et al. [34]	Synthesis and characterization of stationary nanofluids
Wen et al. [35]	Nanofluids formulation, nanofluids applications and mechanistic understanding were detailed
Kakaç and Pramuanjaroenkij [36]	Enhancement of the forced convection heat transfer with nanofluids
Chandrasekar and Suresh [37]	Possible mechanisms that contribute to enhance thermal conductivity of nanofluids
Paul et al. [38]	Several techniques for the measurement of thermal conductivity of nanofluids A unique thermal conductivity measurement device based on the thermal comparator principle was developed
Godson et al. [39]	Experimental and theoretical studies on forced and free convective heat transfer in nanofluids, their thermophysical properties and their applications
Sarkar [40]	Correlations for friction factor and heat transfer characteristics of nanofluids in forced and free convection flow
Mohammed et al. [41]	Types, properties, heat transfer characteristics and limitations towards the application of nanofluids Heat transfer and fluid flow characteristics in microchannels heat exchanger was also described
Mohammed et al. [42]	The heat transfer enhancement, nanofluids preparation technique, types and shapes of nanoparticles, base fluids and additives, transport mechanisms, and stability of the suspension were discussed
Saidur et al. [43]	Applications and challenges of nanofluids have been compiled and reviewed
Saidur et al. [44]	Heat transfer performance of different nanorefrigerants, pressure drop and pumping power of a refrigeration system with nanorefrigerants, pool boiling heat transfer performance of refrigerant were reported
Murshed et al. [45]	Boiling, spreading, and convective heat transfers of nanofluids
Ghadimi et al. [46]	Stability, characterization, analytical models and measurement techniques, thermal conductivity and viscosity aspects
Kleinstreuer and Feng [47]	Experimental and theoretical studies of nanofluid thermal conductivity enhancement
Han and Fin [48]	Thermal conductivity of CNTs and their polymer nanocomposites

at volume concentration of 0.3% was observed. These results show that the enhancement in the effective thermal conductivity of very dilute Al_2O_3/water nanofluids was not remarkable.

Chandrasekar et al. [50] presented an experimental investigation of determination of effective thermal conductivity of Al_2O_3/water nanofluid. The thermal conductivity enhancements of current Al_2O_3/water nanofluids are 1.64%, 3.28%, 3.43%, 7.52% and 9.7%, correlated to volume concentrations of 0.33%, 0.75%, 1%, 2% and 3%. A linear relationship between the thermal conductivity enhancement and volume concentration was attributed to large regions of particle-free liquid with high thermal resistances created by highly agglomerated nanoparticles. They have also indicated that the relationship between the thermal conductivity enhancement and volume concentration is usually nonlinear for nanoparticles with a high aspect ratio (such as nanotube, nanorod, etc.) or nanoparticle alignment.

Paul et al. [51] synthesized Al–5 wt% Zn nanoparticles by mechanical alloying and are dispersed to the tune of 0.01–0.10% volume concentration in ethylene glycol (base fluid) following a careful mixing protocol. Thermal conductivity of the nanofluids and base fluid has been measured using the transient hot-wire method. It is observed that thermal conductivity of the nanofluids strongly depend on the concentration, particle size, fluid temperature and stability of dispersed nanoparticles in the base fluid. A maximum of 16% enhancement in thermal conductivity has been recorded at a volume concentration of 0.10%. It was pointed out that Al–5 wt% Zn alloy is a new material that can be used as a dispersoid for nanofluid preparation. The level of enhancement recorded in this study at a much lower concentration surpasses earlier studies with comparable systems.

Duangthongsuk and Wongwises [52] reported the thermal conductivity of TiO_2/water nanofluids with volume concentration of 0.2–2%. It was clearly shown that the use of nanoparticles dispersed in base liquid gave greater thermal conductivity than the base fluid, about 3–7% for the volume concentration range between 0.2% and 2%.

Li et al. [53] experimentally investigated the effect of two types of magnetic nanoparticle on the thermal conductivity of magnetic fluids. They used Fe_3O_4/water and Fe/water magnetic fluid. The average particle diameter for Fe_3O_4 is 20 nm while that of Fe is 26 nm. Compared with pure water, the thermal conductivity of Fe/water magnetic fluid increased by about 14.9% at 5% volume concentration. They also illustrated that the thermal conductivity of Fe/water magnetic fluid increases with the strength of the external magnetic field and the thermal conductivity of water experienced almost no variation under the same external magnetic field. In addition they demonstrated that the application of the magnetic field enhances energy transport process in the magnetic fluid. For the Fe/water magnetic fluid of 5l% volume concentration, its thermal conductivity was 0.667 W/m K under the field strength of 35 G while the thermal conductivity of the sample fluid was 0.833 W/m K under the field strength of 240 G.

Yu et al. [54] observed that the thermal conductivity of kerosene based Fe_3O_4 nanofluids increased almost linearly with volume concentration of the nanoparticles. When the volume concentration was 1%, the enhancement value was up to 34%, which was higher than that of Fe_3O_4 aqueous nanofluid. Kerosene based Fe_3O_4 nanofluids prepared did not showed the time-dependence of the thermal conductivity characteristic, which indicated a good suspension stability of the nanofluids prepared by them. In order to investigate the effect of temperature on the enhancement of the thermal conductivity, the thermal conductivities were measured in the temperature range of 10–60 °C. The results indicated that the absolute thermal conductivities increased with the increasing temperature with the enhanced ratios being almost constant. Thus it was concluded that the thermal conductivities of the nanofluids track the thermal conductivities of the base liquid.

Thermal transport properties of ethylene glycol based nanofluids containing low volume concentration diamond nanoparticles (DNP/EG nanofluid) have been reported by Yu et al. [55]. The thermal conductivity enhancement ratio of DNP–EG nanofluid at a volume concentration of 1% was up to 17.23%. Moreover, it was found that the thermal conductivity enhancement decreased with elapsed time at pH 7. While for the stable DNP/EG nanofluids at pH 8.5, there was no obvious thermal conductivity decrease for 6 months. Hence they illustrated that the thermal conductivity enhancement was correlated with the pH values of the suspensions and the pH value has a direct effect on the stability of nanofluids. It was also mentioned that the thermal conductivity enhancement values DNP/EG nanofluids are much larger than those containing metallic oxide.

Thermal conductivity enhancements of nanodiamond particles suspended in pure deionized water with different volume concentrations in the range from 0.8% to 3% have been measured by Yeganeh et al. [56]. The highest observed enhancement in the thermal conductivity was 7.2% for a volume fraction of 3% at a temperature of 30 °C. The thermal conductivity increased by about 9.8% when the temperature was raised to 50 °C.

Jahanshahi et al. [57] measured the thermal conductivity of SiO_2/water nanofluid having volume concentrations ranging from 1% to 4% with a transient hot-wire method. The thermal conductivity of nanofluid increased linearly with increasing particle volume concentration. The measured thermal conductivity of SiO_2 nanofluid was 3.23% and 23% at a volume fraction of 1% and 4%, respectively.

The degree of thermal conductivity enhancement of the nanofluid (with respect to the base fluid) as a function of volume concentration and size of gold nanoparticle has been determined using the transient hot-wire technique by Paul et al. [58]. They observed that the degree of enhancement increases with increase in concentration and decrease in size of nanoparticles. The maximum enhancement recorded was 48% at 0.00026% volume concentration and 21 nm average particle size.

Experimental investigations have been carried out by Vajjha and Das [59] for determining the thermal conductivity of three nanofluids containing Al_2O_3, CuO and ZnO nanoparticles dispersed in a base fluid of 60:40 (by mass) ethylene glycol and water mixture. Particle volumetric concentration tested was up to 10% and the temperature range of the experiments was from 25 °C to 80 °C. They observed an increase in the thermal conductivity of nanofluids compared to the base fluids with an increasing volume concentration of nanoparticles. The thermal conductivity also increased substantially with an increase in temperature. At room temperature, maximum thermal conductivity enhancement observed with nanofluids containing Al_2O_3, CuO and ZnO nanoparticles were 35%, 32% and 17% respectively.

Substantial thermal conductivity enhancements were seen for ethylene glycol (EG) based copper nanofluids by Yu et al. [60]. The enhancement ratios of the Cu/EG nanofluids with the volume concentration of 0.3% were 5%, 11% and 33% at 10 °C, 25 °C and 50 °C respectively. The corresponding enhancement ratios with the volume concentrations of 0.5% were 8%, 16% and 46% at 10 °C, 25 °C and 50 °C respectively. Since the thermal conductivities strongly depend on the temperature of fluid, and the enhancement ratios increased with the increasing temperatures. Hence they suggested Brownian motions of Cu nanoparticles would play the key role on determining thermal conductivity enhancement of nanofluids.

Habibzadeh et al. [61] studied the stability and thermal conductivity of nanofluids of SnO_2/water nanofluids at weight concentrations of 0.012%, 0.018% and 0.024%. The thermal conductivities of nanofluids are enhanced with increase of the SnO_2

nanoparticles weight concentration. The maximum thermal conductivity enhancement of 7% is observed at the 0.024% weight concentration of the suspension. It was shown that the thermal conductivity enhancement depends upon the pH value, nanoparticles concentration and temperature. The results also show that there are more surface charges at a pH value of 8, at which the thermal conductivity is higher.

The thermal conductivity of ethylene glycol (EG) and propylene glycol (PG) based AlN nanofluids were measured by Yu et al. [62]. AlN nanoparticles, with an average diameter of about 50 nm were used. However, the measured average particle size in the formulated nanofluids is found to be much larger than that of the primary particles. The average particle sizes for AlN–EG and AlN–PG nanofluids were 165 nm and 169 nm respectively which revealed that the nanoparticles formed clusters. Substantial increases in thermal conductivity were noted for the nanofluids investigated, with thermal conductivity enhancement ratios of 38.71% and 40.2% for EG and PG based nanofluids respectively at 10% volume concentration of nanoparticles. The existence of approximately linear relationship between the thermal conductivity enhancement ratio and the volume fraction of AlN nanoparticles was reported. They also demonstrated that the increase in thermal conductivity enhancement ratios of AlN/EG and AlN/PG nanofluids was not appreciable in the temperature range of 10–60 °C and they track the thermal conductivity trends of the base fluids.

Thermal conductivity of transformer oil based nanofluid containing Al_2O_3 powders (spherical and rod shaped) and AlN powders were measured by Choi et al. [11]. The thermal conductivity of suspended spherical-shape Al_2O_3 in transformer oil showed an enhancement of more than 20% at 4% volume concentration of nanoparticles. But the thermal conductivity enhancement is greatly higher for AlN–oil nanofluid compared with Al_2O_3 fluids. For AlN nanoparticles at a volume concentration of 0.5%, thermal conductivity is enhanced by 8%. It is concluded that the rod-shaped particle is favorable for the heat transfer compared with the spherical-shaped particle.

Sharma et al. [63] experimentally investigated the enhancements of the thermal conductivity of silver/ethylene glygol nanofluid as a function of the concentration of silver. There was approximately 10% improvement in thermal conductivity of nanofluids when the nanofluid concentration is about 1000 ppm. On the other hand, when the concentration of silver nanoparticles is increased to 5000 ppm and 10,000 ppm, the thermal conductivity increased to 16% and 18% respectively. As the increase in thermal conductivity with increasing volume concentration of silver is not significant, it is concluded that the thermal conductivity with 10,000 ppm concentration did not show significant improvement as compared with 1000 ppm and 5000 ppm concentration. Hence they concluded that the high concentration of particles seems to hinder the enhancement effect due to the aggregation of silver particles. They also observed the enhancements in thermal conductivities of Ag/ethylene glygol nanofluids to decrease as time lapsed. After 30 days of preparation, the thermal conductivity of 1000 ppm and 5000 ppm silver nanofluids decreased slightly from 10% and 16% to 9% and 14%, respectively. On the other hand, the thermal conductivity of 10,000 ppm nanofluid decreased from18% to 14% after 30 days. It is reported that the silver particles were aggregated in early stage of preparation (up to 15 days), which leads to the increase in the size of silver particles.

Thermal conductivity of Al–Cu/EG nanofluid was presented by Chopkar et al. [64]. The results indicated that the nanofluids containing a small volume fraction of nanoparticles have significantly higher thermal conductivity (up to two times) that of the base liquids without nanoparticles. This was attributed to the higher thermal conductivity and composition of the solid dispersoids. They observed a sharp increase between 0.75% and 1.5% volume concentration of particles. The increase was over 200% with merely 1.5% volume concentration of particles. Though the conductivity ratio increased with volume concentration, the stability of the nanofluid was adversely affected due to sedimentation and inhomogeneity beyond a volume concentration of 1.5%.

Nanofluids containing Al_2O_3, ZnO, TiO_2 and MgO nanoparticles were prepared with a mixture of 55% distilled water and 45% ethylene glycol as base fluid and the thermal conductivity were measured by Xie et al. [65]. At a volume concentration of 1%, the increase in thermal conductivities of nanofluids containing Al_2O_3, ZnO, TiO_2, and MgO nanoparticles were 4%, 3.5%, 2% and 4.5% respectively. At the same volume fraction and flow condition, the enhancements in heat transfer coefficients of Al_2O_3 and ZnO nanofluids were 40% and 18% respectively while that of TiO_2 and MgO were 10% and 252% receptively. But from the well-established heat transfer theories, for a fully developed inner-tube laminar flow with constant wall temperature, the enhancements in heat transfer coefficients would be the same to the thermal conductivity enhancement ratio. Hence, enhancements in heat transfer coefficients would not exceed 5%. As the experimental results showed intriguingly higher increase in heat transfer coefficients as several tens even hundreds percent, they concluded that the single phase correlation with nanofluid properties was not able to predict nanofluids heat transfer coefficients and increasing thermal conductivity was not the only mechanism responsible for the heat transfer enhancement and other factors such as dispersion, chaotic movement of nanoparticles, Brownian motion and particle migration might be the reasons for dramatic increase in heat transfer coefficients.

Chopkar et al. [66] synthesized Al_2Cu and Ag_2Al nanoparticles by mechanical alloying and then prepared nanofluids by dispersing about 0.2–1% volume concentration of these nanoparticles in water and ethylene glycol. They also characterized the size/microstructure of nanoparticles by X-ray diffraction and transmission electron microscopy and measured the thermal conductivity of nanofluids. The results indicated that the nanofluids records 50–150% improvement in thermal conductivity. It was also noted that water-based nanofluids recorded greater ability to transfer or conduct heat than that by ethylene glycol based nanofluids with comparable volume fraction of Al_2Cu nanoparticles. However, ethylene glycol based nanofluid seems to possess greater stability of dispersion (resistance to sedimentation and clogging) than that of the water-based one due to higher viscosity of the former than the latter. Both experimental results and analytical study indicate that the degree of enhancement strongly depends on identity/composition, size, volume fraction and shape (aspect ratio) of the dispersed nanoparticles.

Wei et al. [67] have recently developed a single-step chemical method known as chemical solution method (CSM) to vary and manipulate nanofluid microstructures effectively through adjusting synthesis parameters like the reactant concentration and pH value. They applied this method to synthesize two kinds of novel cuprous oxide (Cu_2O) nanofluids namely (i) suspensions of spherical Cu_2O nanoparticles in water and (ii) suspensions of octahedral Cu_2O nanoparticle in water. For both types of nanofluids, the measured thermal conductivity showed a high nonlinearity to both the molar concentration and the temperature. The measured data revealed that the conductivity enhancement with spherical Cu_2O nanoparticles is higher than that with octahedral Cu_2O nanoparticles. Variation in the $CuSO_4$ molar concentration has led to a change in nanofluid thermal conductivity through the change in nanofluid microstructure. An extraordinary conductivity enhancement of 24% was noticed for both types of nanofluids.

Again with CSM, Wei et al. [68] synthesized CuS/Cu_2S nanofluids having either core–shell or hollow structure and presented experimental evidence that nanofluid thermal conductivity can be either

increased or decreased by the presence of nanoparticles. This was attributed to a phenomenon predicted by the recent thermal-wave theory of nanofluids. However, the conductivity ratio was larger than one for most nanofluids with hollow structure. Depending on factors like material properties of nanoparticles and base fluids, nanoparticle's geometrical structure and their distribution in the base fluids, interfacial properties and dynamic processes on particle–fluid interfaces, the heat diffusion (at nanoscale level) and thermal-wave (at macro scale level) may either enhance or counteract each other. Consequently, the heat conduction may be enhanced or weakened by the presence of nanoparticles.

Li et al. [69] focused on the effect of pH and sodium dodecyl benzene sulfonate (SDBS) surfactant on the thermal conductivity of Cu/H_2O nanofluids. Their results showed that the thermal conductivity enhancements of Cu/H_2O nanofluids are highly dependent on the weight fraction of nanoparticle, pH values and SDBS surfactant concentration of nano-suspensions. The particle size distributions of Cu/H_2O nano-suspensions in the absence and presence of SDBS surfactant showed that there are obvious variations in the particle size characteristics between two samples. The average particle sizes obtained are 6770 nm and 207 nm in the absence and presence of SDBS surfactant respectively. Therefore, it was concluded that the stabilization of Cu/H_2O suspension with SDBS surfactant is better. Therefore, they recommended the combined treatment with both the pH and chemical surfactant to improve the thermal conductivity for practical applications of nanofluid. For Cu nanoparticles, at a weight fraction of 0.1%, thermal conductivity was enhanced by up to 10.7% with an optimal pH value and SDBS concentration for the highest thermal conductivity.

Hwang et al. [70] conducted thermal conductivity measurements on various nanofluids containing nanoparticles such as multiwalled carbon nanotube (MWCNT), copper oxide and silicon dioxide dispersed in various base fluids such as water, ethylene glycol and mineral oil. They observed that MWCNT nanofluid has the highest thermal conductivity enhancement among water-based nanofluids whereas SiO_2 nanofluid has the lowest one. From this result, it was shown that the thermal conductivity enhancement of nanofluid depends on the suspended particles. Also, it was shown that MWCNT/oil nanofluid has higher thermal conductivity enhancement than MWCNT/water. Similarly it was shown that CuO/ethylene glycol nanofluid has higher thermal conductivity enhancement than CuO/water. These results imply that higher thermal conductivity enhancement can be obtained for base fluid of lower thermal conductivity. From the results, it was concluded that thermal conductivity enhancement of nanofluid depends on the thermal conductivity of base fluids and suspended particles.

Paul et al. [38] presented the results of thermal conductivity ratio for nanofluids containing ZrO_2 and TiO_2 nanoparticles dispersed in base fluid water and ethylene glycol. The results showed significant increase in the thermal conductivity ratio with increase in volume percent for both ZrO_2 and TiO_2 based nanofluids. The increase for ethylene glycol based nanofluids in both cases is more compared to water-based nanofluids as the former is a more viscous fluid. It was also observed that the ethylene glycol based nanofluids are more stable than the water-based nanofluids. The increase in thermal conductivity ratio is almost linear with increase in volume percent and reaches about 200% for ethylene glycol based ZrO_2 nanofluids.

Godson et al. [71] presented an experimental investigation on the thermal conductivity and viscosity of silver-deionized water nanofluid. Nanofluid is studied for 0.3%, 0.6%, and 0.9% of volume concentrations and for temperatures between 50 °C and 90 °C. A minimum and maximum enhancement of 27% at 0.3% volume concentration and 80% at 0.9% volume concentration were observed at an average temperature of 70 °C. The effect of Brownian motion and thermophoresis on the thermophysical properties was also discussed. They demonstrated that for every increase in concentration of 0.3%, the Brownian velocity increase by 40–60% and the thermophoretic velocity increase by 40–80%. Hence they concluded that out of these two mechanisms, thermophoretic velocity may play a significant role than the Brownian velocity in thermal conductivity enhancement of nanofluids.

Thermal conductivity of nanofluids containing carbon nanotube (CNT) has also been the focus of numerous investigators. Investigation on measurements confirmed conductivities of about 3000 W/m K for multiwalled carbon nanotubes (MWCNTs) [72] and above 2000 W/m K for single-walled carbon nanotubes (SWCNTs) [73]. Thermal conductivity of carbon nanotubes comprising magnetically sensitive metal oxides in heat transfer nanofluids was investigated by Hong et al. [74]. They observed that upon extended exposure to the magnetic field, the mixture slowly vibrated making the nanoparticles to straighten and align with respect to the magnetic field. The aligned nanoparticle chains appeared to be continuous and unbroken, forming a combination of aligned particles and clusters. Time dependent thermal conductivity experiments indicate that the alignment process dominates the thermal conductivity enhancement as opposed to micro convection. Thermal conductivity of stable silicone oil based nanofluids containing CNT has been reported by Chen and Xie [75]. Thermal conductivity results of the CNT nanofluids reveal that the collective effects involving straightness ratio, aspect ratio, and aggregation play a key role in the thermal conductivity of CNT nanofluids.

Wen and Ding [76] investigated the effect of temperature on the thermal conductivity of MCNTs (20–60 nm in diameter and a few tens of micrometers in length)/water nanofluids. For temperatures lower than 30 °C, an approximately linear dependence of thermal conductivity enhancement on temperature was obtained. Ding et al. [77] also showed that the effective thermal conductivity increases with increasing temperature in CNT/water suspensions.

Liu et al. [78] measured the thermal conductivities of nanofluids containing CNTs dispersed in ethylene glycol and synthetic engine oil. The increase of thermal conductivity is up to 12.4% for CNT/ethylene glycol suspensions at 1% volume concentration and 30% for CNT-synthetic engine oil suspensions at 2% volume concentration. It was concluded that the thermal conductivity is highly dependent on important factors such as the structure of the CNTs, clustering, temperature, etc.

Murshed et al. [79] measured the effective thermal conductivity of nanofluids containing titania nanorods of 10 nm diameter and 40 nm length and observed an enhancement of about 30% in the effective thermal conductivity. Chen et al. [80] also carried out experiments to investigate the effective thermal conductivity of aqueous titanate nanofluids. Their results show a small thermal conductivity enhancement of about 3% at 25 °C and about 5% at 40 °C for 2.5% weight concentration of nanofluid. They demonstrated that the aspect ratio of the titanate nanotubes of approximately 10 is not sufficiently large to give a high thermal conductivity enhancement and the shape factor imposes more effect on the convective heat transfer.

Table 3 shows the summary of the experimental works on thermal conductivity of various nanofluids. To avoid repetition and for the sake of brevity, the research works done on thermal conductivity of nanofluids of same type by several other investigators have not been listed in Table 3. The review on the thermal conductivity of nanofluids reveals that a long list of physical phenomenon has been proposed to explain the experimentally observed increase in thermal conductivity of nanofluids. The list includes volume concentration, size of the nanoparticles, higher specific surface area, effect of temperature that causes Brownian motion, magnetic field causing controlled nanoparticle particle alignment, formation of clusters or aggregates and the pH value favoring stability of the suspension. Earlier, Keblinski et al. [81] proposed four possible

Table 3
Summary of the experimental works on thermal conductivity of various nanofluids.

Researcher	Nanofluid	Particle size (nm)	Volume concentration (%)	Maximum enhancement (%)	Findings
Lee et al. [49]	Al_2O_3/water	30 ± 5	0.01–0.3	1.44	Thermal conductivities of the dilute Al_2O_3–water nanofluids increase nearly linearly with the concentration
Chandrasekar et al. [50]	Al_2O_3/water	43	0.33–3	9.7	A linear relationship between the thermal conductivity enhancement and volume concentration was observed
Paul et al. [51]	$Al_{95}Zn_{05}$/EG	50–80	0.01–0.10	16	Nonlinear increase in thermal conductivity ratio of nanofluids was observed and the increase was size attributed to increase in specific surface area in nanoparticles with the decrease in crystallite/grain size
Duangthongsuk and Wongwises [52]	TiO_2/water	21	0.2–2	7	Thermal conductivity is a function of temperature and particle volume concentration
Li et al. [53]	Fe/water	26	1–5	14.9[a] 25[b]	Application of the magnetic field enhances energy transport process in the magnetic fluid
Yu et al. [54]	Fe_3O_4/kerosene	15	0.1–1	34	Clusters formed by nanoparticles aggregation are the main reason for the enhancement of thermal conductivity of nanofluids
Yu et al. [55]	Diamond/EG	5–10	0.1–1	17.23	Thermal conductivity enhancement was correlated with the pH values of the suspensions
Yeganeh et al. [56]	Diamond/water	10	0.8–3	7.2 at 30 °C 9.8 at 50 °C	Dependence of effective thermal conductivity on temperature reveals the difference in the quality of the interactions between the particles
Jahanshahi et al. [57]	SiO_2/water	12	1–4	23	Interactions between solid and adjacent liquid at the interface enhance thermal conductivity of nanofluids
Paul et al. [58]	Au/water	21	$0.6 \times 10^{-4} - 2.6 \times 10^{-4}$	48	Enhancement may be due extremely large specific surface area
Vajjha and Das [59]	Al_2O_3/EG and water CuO/EG and water ZnO/EG and water	53 29 29	1–10 1–6 2 and 4	35 32 17	Nanofluids exhibit enhanced thermal conductivity with an increase in temperature, hence their application in higher temperature environment will be more beneficial
Yu et al. [60]	Cu/EG	5–10	0.3 and 0.5	46 at 50 °C	The thermal conductivities strongly depend on the temperature of fluid, and the enhancement ratios increased with the increasing temperatures suggesting Brownian motions of Cu nanoparticles
Habibzadeh et al. [61]	SnO_2/water	4.3–5.3	0.012–0.024 (wt%)	7	Thermal conductivity enhancement depends upon the pH value, nanoparticles concentration and temperature
Yu et al. [62]	AlN/EG AlN/PG	50	1–10	38.71 40.2	A linear relationship exists between the thermal conductivity enhancement ratio and the volume concentration. The increase in thermal conductivity enhancement ratios was not appreciable and they track the thermal conductivity trends of the base fluids
Choi et al. [11]	Al_2O_3/transformer oil AlN/transformer oil	$13/2 \times 100 - 1000$ 50	0.5–4 0.5	20 8	Enhancement is almost twice the value of the Al_2O_3/water nanofluid
Sharma et al. [63]	Ag/EG	100–500[c]	1000–10,000 ppm	18	The thermal conductivity of nanofluid can be influenced by nanoparticle concentration. It is postulated that the particles aggregate more rapidly, as the concentrations are increased. The thermal conductivity enhancement depends on the volume fraction of the suspended particles, thermal conductivities of the particles and base fluids

Table 3 (*Continued*)

Researcher	Nanofluid	Particle size (nm)	Volume concentration (%)	Maximum enhancement (%)	Findings
Chopkar et al. [64]	Al–Cu/EG	20–40	0.2–2	120	The increase in conductivity is a function of size, volume fraction and thermal property of the solid suspension The stability of the nanofluid was adversely affected due to sedimentation and in homogeneity beyond a volume concentration
Xie et al. [65]	Al_2O_3/DW-EG ZnO/DW-EG TiO_2/DW-EG MgO/DW-EG	30 ± 5	1	4 3.5 2 4.5	Thermal conductivity increase was not the only mechanism responsible for the heat transfer enhancement and other factors such as dispersion, chaotic movement of nanoparticles, Brownian motion and particle migration might be the reasons for dramatic increase in heat transfer coefficients
Chopkar et al. [66]	Al_2Cu/H_2O Al_2Cu/EG Ag_2Al/H_2O Ag_2Al/EG	20–80	2.5	150 120 175 140	Nanofluids containing small volume fraction of nanoparticles induce significantly higher thermal conductivity than that of the base liquid without nanoparticles
Wei et al. [67]	Cu_2O/H_2O (spherical) Cu_2O/H_2O (octahedral)	200.5 –	0.5 0.02 (Molar volume concentration)	24	Nanofluid thermal conductivity can be controlled by either controlling the microstructure during synthesis or its temperature
Wei et al. [68]	CuS/Cu_2S/ammonium acetate	100	0.03 (Molar volume concentration)	20	Nanoparticle's geometrical structure affects the thermal conductivity ratio of nanofluids. With core–shell structure it varied from 0.82 (smaller than 1) to 1.21 (larger than 1) while the ratio was larger than 1 for nanofluids with hollow structure
Li et al. [69]	Cu/H_2O	207	0.1 (weight fraction)	10.7	Control of with both the pH and chemical surfactant is recommended to improve the thermal conductivity for practical applications of nanofluid
Hwang et al. [70]	MWCNT/H_2O MWCNT/oil CuO/H_2O CuO/EG SiO_2/H_2O	(10–30 m) × (10–50) μm 33 33 12	1 0.5 1 1 1	7 8.5 5 9 3	Thermal conductivity enhancement of nanofluid depends on the thermal conductivity of base fluids and suspended particles
Paul et al. [38]	ZrO_2/H_2O TiO_2/H_2O ZrO_2/EG TiO_2/EG	20 50 20 50	0–2.2 0–2 0–2.2 0–2	60 37 200 33	The increase in thermal conductivity for ethylene glycol based nanofluids in is more compared to water-based nanofluids
Godson et al. [71]	Ag/H_2O	<100	0.3, 0.6, 0.9	30 at 50 °C	Thermophoretic velocity may play a significant role than the Brownian velocity in thermal conductivity enhancement of nanofluids

[a] In the absence of magnetic field.
[b] In the presence of magnetic field.
[c] Time dependent size.

mechanisms for enhanced thermal conductivity of nanofluids namely (i) Brownian motion of the nanoparticles (ii) nanolayering of the liquid at the liquid/particle interface (iii) the nature of heat transport in the nanoparticles, and (iv) clustering of nanoparticles. As a result, several theoretical models have been proposed by taking into account the effect of Brownian motion [82–86], nanolayer [87–89] and clustering [90–92]. From the experimental works on thermal conductivity of nanofluid, it becomes apparent that smaller sized nanoparticles could bring Brownian motion at higher temperatures and the microstructure of the nanofluid provide details regarding the alignment of the nanoparticles or the cluster formation but there is no sufficient experimental technique to prove the presence of nanolayer and the value of its thickness. On the other hand, measurement of pH together with zeta potential will provide the information regarding stability of the prepared nanofluid. It is the fact that if the pH value is maintained away from the isoelectric point (pH value where the repulsive forces between the particles becomes zero), the particles will be well dispersed in the fluid avoiding sedimentation and improving the stability and thermal conductivity of nanofluid. It is also obvious that with the help of magnetic field it becomes easy to control the structure of nanoparticles suspended in the magnetic fluids. Thus, the future experimental works on the investigation of thermal conductivity of nanofluid must provide an experimental evidence to justify the reason attributed for enhancement in thermal conductivity.

2.2. Viscosity of nanofluids

While the thermal conductivity of nanofluids is important for heat transfer applications, viscosity is also important in designing nanofluids for flow and heat transfer applications because the pressure drop and the resulting pumping power depend on the viscosity. Compared to the works on thermal conductivity of

nanofluids, only lesser investigations have been reported on the rheological behavior of nanofluids.

The effective viscosities of the Al_2O_3/water nanofluids were measured using a viscometer of oscillation type by Lee et al. [49]. The effective viscosities of Al_2O_3/water nanofluids with low concentrations from 0.01% to 0.3% were measured in the temperature range from 21 °C to 39 °C. They showed the effective viscosities of Al_2O_3/water nanofluids significantly decrease with increasing temperature and increase with increasing volume concentration. They also observed that the alumina nanofluids have a nonlinear relation between their viscosity and volume concentration. Nonlinear behavior was attributed to the particle–particle interactions and the increased surface of well dispersed nanoparticles in the nanofluids.

A maximum increase in viscosity of Al_2O_3/water nanofluids was 2.36 times that of water at 5% volume concentration as observed by Chandrasekar et al. [50]. The results show that the relative viscosity increase was almost linear up to 2% volume concentration. However, at volume concentrations more than 2%, the increase in relative viscosity shows a nonlinear relationship with volume concentration. This was attributed to the hydrodynamic interactions between particles which become important as the disturbance of the fluid around one particle interacts with that around other particles at higher volume concentrations.

Duangthongsuk and Wongwises [52] experimentally determined the viscosity of TiO_2–water nanofluids as a function of particle volume concentration and temperature. The results indicate that the viscosity of nanofluids significantly increases with decreasing nanofluid temperature and also increases with increasing particle volume concentration. It is obvious that the viscosity of nanofluids is higher than the base fluid by about 4–15%.

Li et al. [53] measured the viscosity of the magnetic fluid under the applied magnetic field. The measured results have indicated that the viscosity of the magnetic fluids increases with the concentrations of the suspended magnetic particles and the surfactant. The strength and orientation of the externally applied magnetic field play remarkable roles in affecting the viscosity of the magnetic fluid. This parameter increased with the strength of the external magnetic field. For the same magnetic fluid, its viscosity in the presence of a magnetic field perpendicular to the main flow is larger than that in the presence of a parallel field for the same field strength.

Yu et al. [62] conducted rheological study on nanofluids containing AlN nanoparticles suspended in ethylene glycol and propylene glycol. They demonstrated that for AlN fraction below 5%, the two nanofluids behaved as Newtonian liquids, though beyond 5% volume concentration, the nanofluids demonstrated the shear-shinning behavior, which was intensified for lower temperatures and lower shear rates. The AlN volume fraction $\theta = 0.05$ is considered a critical concentration of rheological behavior. Differentiation between Newtonian and non-Newtonian behaviors of the nanofluids depends strongly on the kinds and the shapes of nanoparticles, their volume fractions and temperature.

Godson et al. [71] presented an experimental investigation on viscosity of silver-deionized water nanofluid. Nanofluid consisted of silver nanoparticles of 0.3%, 0.6%, and 0.9% of volume concentrations and studied for temperatures between 50 °C and 90 °C. A minimum and maximum enhancement of 8% at 0.3% volume concentration and 28% at 0.9% volume concentration respectively were observed at 50 °C. Viscosity are correlated as quadratic functions of volume concentration. The viscosity ratio for nanofluid with 0.3% volume concentration increased from 1.06 to 1.2, and for nanofluid with 0.9% volume concentration, the ratio increased from 1.23 to 1.43 for the temperature range between 50 °C and 90 °C.

Kang et al. [93] measured the viscosities of UDD (ultra dispersed diamond)/ethylene glycol, silver/water, and silica/water nanofluids. They found that the viscosity increase was 50% for UDD/EG nanofluid, 30% increase for silver/water and 20% increase for silica/water nanofluids at volume concentrations of 1%, 2% and 3% respectively.

Prasher et al. [94] demonstrated that the viscosity of alumina/propylene glycol (PG) nanofluids was independent of shear rate, proving that the nanofluids are Newtonian in nature and increases as nanoparticle volume concentration increases. They found a 30% increase in viscosity at 3% volume concentration and attributed this increase to aggregation of the nanoparticles in the nanofluid with the size of the aggregates around three times the size of the individual nanoparticles.

Namburu et al. [95] presented an experimental investigation of rheological properties of copper oxide nanoparticles suspended in 60:40 (by weight) ethylene glycol and water mixture. Nanofluids of volume concentration ranging from 0% to 6.12% were tested. The experiments were also carried over temperatures ranging from −35 °C to 50 °C to demonstrate their applicability in cold regions. For the particle volume concentrations tested, nanofluids exhibited Newtonian behavior. The viscosity of nanofluids increased with increase in volume concentration of nanoparticles. They reported that the viscosity of 6.12% volume concentration nanofluid is about four times the value of the base fluid at −35 °C. The viscosity of copper oxide nanofluids decreased exponentially with increase in the temperature.

Schmidt et al. [96] presented experimental shear and longitudinal viscosity data on two nanofluid systems namely Al_2O_3/decane and Al_2O_3/isoparaffinic polyalphaolefin (PAO). Their shear viscosity data exhibited an enhancement over the Einstein model and the longitudinal viscosity data indicate that the nanoparticles do not aggregate in these nanofluid systems. When the suspensions are extremely dilute, they show no signs of sedimentation, the results indicated that aggregation may not be responsible for the disagreement between effective medium models and the data in all nanofluid systems, and that the models based on Brownian dynamics or other nanoscale phenomena should be considered.

As organic fluids like EG are more favorable for the dispersion of nanosized particles compared to water, experimental work of Xie et al. [97] showed enhancement ratios of the viscosity of ethylene glycol (EG) based Al_2O_3 suspensions smaller than those of water-based suspensions, indicating the significant influence of the base fluid on the viscosity of the nanofluids. They also studied the dependence of the viscosity on pH values. The isoelectric point is determined to be 9.2 for alumina nanoparticles. When pH is far from this, the nanoparticles are well dispersed because of the very large repulsive forces among the nanopaticles. The repulsion among nanoparticles decreases when pH value is close to isoelectric point. This causes coagulation or aggregation of nanoparticles and the viscosity increases for a nanofluid with pH value close to isoelectric point.

The effect due to temperature and particle volume concentration on the dynamic viscosity for the Al_2O_3/water nanofluid has been experimentally investigated by Nguyen et al. [98]. They found that, in general, nanofluid dynamic viscosity increases considerably with particle volume concentration but decreases with a temperature increase. Their results have revealed the existence of a critical temperature beyond which the particle suspension properties seem to be drastically altered, which, in turn, has triggered a hysteresis phenomenon. The hysteresis phenomenon has raised serious doubts regarding the reliability of using nanofluids for heat transfer enhancement purposes.

Chen et al. [99] carried out experiments on the rheological behavior of EG based titanate nanotubes (TNT) nanofluids containing weight concentrations of 0.5%, 1%, 2%, 4% and 8% TNT at 20–60 °C. Their results showed a very strong shear thinning behavior of the TNT nanofluids and big influences of

particle concentration and temperature. The slopes of the shear viscosity–shear rate curves at the low shear rate region were estimated to be 0.61 and 0.86 for 4% and 8% weight concentrations respectively. It was also shown that the shear viscosity of nanofluids increases with increasing TNT concentration for a given shear rate. It is observed that the relative viscosity at low shear rate region increases sharply with increasing temperature, indicating stronger shear thinning behavior of the EG/TNT nanofluids at higher temperatures. However, the relative viscosities at high shear rates converge to the same constant for all the temperatures investigated. These results suggest different mechanisms for the rheological behavior at low and high shear regions. Hence they categorized the rheological behavior of the EG/TNT nanofluids into four regimes like (i) dilute nanofluids (ii) semi-dilute nanofluids (iii) semi-concentrated nanofluids and (iv) concentrated nanofluids. The demarcation of these regimes depends on the effective particle concentration i.e., the aggregate size.

Anoop et al. [100] considered three types of nanofluids, viz., alumina/water, alumina/ethylene glycol and copper oxide/ethylene glycol to study their rheological properties. Both water-based as well as ethylene glycol based nanofluids exhibited Newtonian behavior. The experiments revealed that with an increase in the particle concentration, the viscosity ratio increases and this increase was more predominant for water-based nanofluids than for ethylene glycol based nanofluids. The increase in viscosity was attributed to the combined effects of electroviscous forces (due to the presence of an electrical double layer with electrostatic stabilization) and particle aggregation.

The dispersion and stability of nanofluids obtained by dispersing Al_2O_3 nanoparticles (obtained from different sources) in water were analyzed by Pastoriza-Gallego et al. [101]. They evaluated the differences arising from different dispersion techniques, the resulting particle size distribution and time stability among the different samples. It has been found that the influence of particle size in viscosity is very large and must be taken into account for any practical application. These viscosity differences were rationalized by considering a theory describing the aggregation state of the nanofluid. The effect of considering variable and constant aggregate size to predict nanofluid viscosity was also investigated by them. They showed that the assumption of constant aggregate size yielded poorer estimations at low concentration while the assumption of variable aggregate size would be desirable at higher concentrations.

Yu et al. [102] demonstrated that when volume concentration of ZnO/EG nanofluid is less than 2%, its viscosity is independent of shear rate from $20\,s^{-1}$ to $100\,s^{-1}$ in the range of 20–60 °C. While for the ZnO/EG nanofluid with volume concentrations more than 3%, the shear-shinning behavior was observed. These facts show that ZnO–EG nanofluids with volume concentrations less than 3% had non-Newtonian behaviors. It is concluded that the ZnO/EG nanofluids with the higher volume concentration exhibited different rheological behaviors from those with lower volume concentration.

Rheological behavior of agglomerated silver nanoparticles suspended in diethylene glycol over a wide range of volume concentrations was studied by Tamjid and Guenther [103]. The nanoparticle suspensions generally exhibited a yield pseudoplastic behavior. The strong dependency of relative viscosity on the volume concentration suggested that the particle interactions (or more specifically, the attractive interparticle potential) become more pronounced with increasing volume concentration. The critical solid loading was estimated to be about 11%.

A linear relation between shear stress and shear rate of diamond/EG nanofluids was noticed by Yu et al. [55] and demonstrated the Newtonian behavior of such nanofluids. Their experiments revealed that with the increase of temperature, the viscosity of nanofluids decreases rapidly. The reason for decrease in viscosity with the increase in temperature was attributed to the weakening effect on the inner-particle/intermolecular forces.

Pastoriza-Gallego et al. [104] experimentally studied nanofluids composed by cupric oxide (CuO) nanoparticles dispersed in water, in a concentration range from 0.05% to 10% in weight fraction. Two different sets of samples were considered for viscosity measurements, one of them obtained from dispersion of commercial dry nanopowder, and the other from dispersion of synthesized (in situ) dry nanopowder.

Kole and Dey [20] presented the experimental results on the viscosity of nanofluid prepared by dispersing alumina in commercial car coolant. They showed that while the pure base fluid display Newtonian behavior over the measured temperature, it transforms to a non-Newtonian fluid with the addition of a small amount of alumina nanoparticles and it behaves as a Bingham plastic with small yield stress. Their results also showed that viscosity of the nanofluid increases with increasing nanoparticle concentration and decreases with increase in temperature. They also demonstrated that the expression considering the influence of Brownian motion of nanoparticles in the base fluid could predict fairly the nanofluid viscosity. The same research group [105] has also presented the experimental results on viscosity of CuO/gear oil nanofluid. The observations presented were same as that of their previous work [20] expect that it was demonstrated that the expression considering aggregation could predict fairly the nanofluid viscosity.

Abareshi et al. [106] were the first to report the rheological properties of nanofluids of α-Fe_2O_3 nanoparticles and glycerol. The experimental results showed that the viscosity of α-Fe_2O_3/glycerol nanofluids increases with increasing the particle volume concentration, decreases with increasing temperature and the nanofluid exhibited non-Newtonian behavior at lower temperatures. They also established that the nanofluid has some yield stress due to addition of nanoparticles to a base fluid.

Tsai et al. [107] investigated the effect of viscosity of the base fluid on the thermal conductivity of nanofluids in which Fe_3O_4 nanoparticles are suspended in the base fluid composed of diesel oil and polydimethylsiloxane. Viscosity of the base fluid is varied by changing the volumetric fractions between both fluids. The measured thermal conductivity of nanofluids gradually approaches the value predicted by the Maxwell equation by increasing the viscosity. It is demonstrated that the viscosity of nanofluids does affect the thermal conductivity of nanofluids, and the Brownian motion of suspended particles could be an important factor that enhances the thermal conductivity of nanofluids.

Wang et al. [108] reported the effects of viscosity of base liquid on the thermal conductivity of nanofluids from the view of Brownian motion. They found that the thermal conductivity of nanofluids decreases with increasing viscosity and approaches a constant value. Based on the previously reported work [107], the authors [108] observed that the viscosity around 100 cP is a critical value of demarcation. Below 100 cP of viscosity, the Brownian motion is active, so the thermal conductivity of nanofluids increases. Over 100 cP of viscosity, the Brownian motion becomes inactive and thermal conductivity decreases.

Timofeeva et al. [109] presented the experimental data for the viscosity of nanofluids with SiC particles suspended in EG/H_2O mixture with a 50/50 volume ratio. It was observed that at the same temperature, particle concentration and pH, the viscosity decreases with the increase in the average particle size. This lower viscosity is highly desirable for heat transfer applications to minimize the pumping power penalties. Comparing the viscosity increase in analogous water- and EG/H_2O-based suspensions reveals a lesser viscosity increase in the EG/H_2O nanofluids. The difference in the viscosity increase is more pronounced at smaller particle sizes. Hence it is reported that the viscosity increase should be independent of the viscosity of the base fluid and only proportional to the

particle volume concentration. The observed phenomena can be related to the difference in the structure and thickness of the diffuse fluid layers around the nanoparticles in various base fluids, which affects the effective volume concentration and ultimately the viscosity of the suspension.

The summary of the experimental investigation on the viscosity of various nanofluids is given in Table 4. It is learnt that the viscosity of the nanofluid may increase linearly or nonlinearly due to the addition of nanoparticles as the particle interactions become more prominent with increasing volume concentration. The viscosity of nanofluid decreases with the increase in temperature which was attributed to the weakening effect on the inner-particle/intermolecular forces. The fact, namely, the decrease in viscosity with increase in temperature will be favorable for its application in thermal management systems. However the phenomenon of hysteresis reported by Nguyen et al. [98] is required to be considered to ensure reliable and successful application of nanofluid in heat transfer systems. Furthermore, the review on the experimental nanofluid viscosity data indicates that nanofluid may exhibit Newtonian or non-Newtonian behaviors which were coupled with the level of volume concentration. It is also revealed that nanofluid with smaller sized nanoparticles shows a significantly larger viscosity due to effects of the electric double layer repulsion. Recent findings of Wang et al. [108] about the decrease of thermal conductivity with increase in viscosity of nanofluid and the limiting viscosity value to decide whether the Brownian motion is active or inactive has created premises for future research works.

2.3. Density of nanofluid

Research work on the density, specific heat and surface tension of nanofluids is very limited compared to that on thermal conductivity and viscosity and hence only few of important works are presented in this article.

Density of nanofluid is proportional to the volume ratio of solid (nanoparticles) and liquid (base fluid) in the system. Since the density of solids is higher than that of the liquids, generally the density of nanofluid is found to increase with addition of nanoparticles to the fluid. In the absence of experimental data, the density of the nanofluids has been reported to be consistent with the mixing theory [110] given by

$$\rho_{nf} = (1-\phi)\,\rho_{bf} + \phi\rho_s \tag{1}$$

where ρ_{nf} = density of nanofluid, ρ_{bf} = density of base fluid, ρ_s = density of solid particles, ϕ = volume concentration.

Sommers and Yerkes [111] measured the density of the Al_2O_3/propanol nanofluid at room temperature using two methods and compared them. In the first method, a hydrometer was used to measure the specific gravity of a fluid sample. In the second method, a fluid sample of known volume was taken and then weighed on a high precision balance. Data collected using these two methods were then averaged and a nearly linear relationship between density and particle concentration was observed. Fig. 1 shows the comparison of measured and calculated densities which indicate that the differences between them increase with increase in concentration of particles. However the difference is less than 5% when the weight concentration is up to 5%. In the absence of substantial works on density of nanofluids, it is obvious that further research works are clearly required to check the validity of equation based on mixing theory in predicting the density of nanofluids.

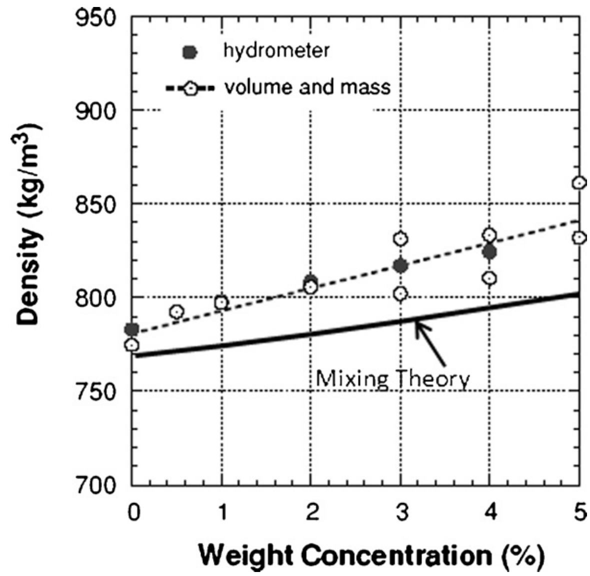

Fig. 1. Comparison of measured and calculated densities of nanofluid [111].

2.4. Specific heat of nanofluid

Typically, the nanofluid's specific heat is smaller than that of the base fluid which implies that for the same temperature increment, heat energy needed is lesser for nanofluid compared to base fluid. In the absence of available experimental data, the following two models have been extensively applied in the experimental and numerical nanofluid investigations to find the specific heat of nanofluid. The first model is one which is analogous to the mixing theory and the specific heat of a nanofluid is expressed as

$$c_{p,nf} = (1-\phi)\,c_{p,bf} + \phi c_{p,s} \tag{2}$$

where the subscripts *nf*, *bf*, and *s* refer to the nanofluid, base fluid and nanoparticle respectively.

Because of its simplicity, Eq. (2) has been used in the assessment of the heat transfer performance of nanofluids by researchers [112–114].

The second model is based on thermal equilibrium mechanism and the specific heat of a nanofluid is expressed as

$$\rho_{nf}c_{p,nf} = (1-\phi)\,\rho_{bf}c_{p,bf} + \phi\rho_s c_{p,s} \tag{3}$$

Eq. (3) has also been adopted in nanofluid investigations [115,116]. In the case that no experimental data are available, it has been believed that both expressions can be considered equivalent and either one may be used to estimate nanofluid specific heat. However, the deviation between the two models is too large to the extent it cannot be ignored as shown in Fig. 2.

Zhou and Ni [117] have presented an experimental investigation of the specific heat of water-based Al_2O_3 nanofluid with a differential scanning calorimeter. Their result indicates that the specific heat of nanofluid decreases gradually as the nanoparticle volume concentration increases. The relationship between them exhibits good agreement with the prediction from the thermal equilibrium model while the simple mixing model fails to predict the specific heat of nanofluid.

Shin and Banerjee [118] observed the average enhancement on the specific heat capacity to be 14.5%. They pointed that the theoretical models based on thermal equilibrium given in Eq. (3) cannot explain the anomalous enhancement of the specific heat capacity at such low concentrations of the nanoparticles (0.6% by volume). This result implies that alternate transport mechanisms exist for nanofluids, thus distinguishing nanofluids from a simple mixture of two materials.

Table 4
Summary of the experimental investigation on the viscosity of various nanofluids.

Researcher	Nanofluid	Particle size (nm)	Volume concentration (%)	Relative viscosity (max)	Findings
Lee et al. [49]	Al_2O_3/H_2O	30 ± 5	0.01–0.3	1.029	Nonlinear relation between their viscosity and volume concentration was attributed to the particle–particle interactions and the increased surface of well dispersed nanoparticles
Chandrasekar et al. [50]	Al_2O_3/H_2O	43	0–5	2.36	Relative viscosity increase was almost linear up to 2% volume concentration and nonlinear at volume concentrations more than 2%, which was attributed to the hydrodynamic interactions between particles
Duangthongsuk and Wongwises [52]	TiO_2/H_2O	221	0.2–2	1.15	Volume concentration and temperature affects viscosity
Li et al. [53]	Fe_3O_4/H_2O Fe/H2O	20 26	0–2.83 0–4	2 11.25[a]	The increment in viscosity is due to the increase of energy dissipation rate occurring during viscous flow due to the presence of the suspended particles
Yu et al. [62]	AlN/EG AlN/PG	50	1–10	38.71 40.2	A Newtonian or non-Newtonian behavior of the nanofluids depends strongly on the kinds and the shapes of nanoparticles, their volume fractions and temperature
Godson et al. [71]	Ag/H_2O	<100	0.3, 0.6, 0.9	1.06–1.43	The viscosity decreases with the increase in temperature and increases with the increase in particle concentrations
Namburu et al. [95]	CuO/EG and H_2O	29	1–6.12	4	At higher concentrations of nanoparticles, relative viscosity diminishes as temperature increases. At lower concentrations, the change in relative viscosity over temperature is minimal
Schmidt et al. [96]	Al_2O_3/decane Al_2O_3/PAO	40	0–1	1.85 1.7	Aggregation may not be responsible for the disagreement between effective medium models and the data in all nanofluid systems, and that models based on Brownian dynamics or other nanoscale phenomena should be considered
Nguyen et al. [98]	Al_2O_3/H_2O	36 47	0–13	4.5 5.5	Existence of a critical temperature beyond which the nanofluid properties seem to be drastically altered
Chen et al. [99]	TNT/EG	10×100	0.1–1.8	1.7	A very strong shear thinning behavior of the TNT nanofluids and big influences of particle concentration and temperature
Anoop et al. [100]	Al_2O_3/H_2O Al_2O_3/EG CuO/EG	95,100 100 152	0–6	1.6–1.8 1.22 1.24	The increase in viscosity was attributed to the combined effects of electroviscous forces and particle aggregation
Pastoriza-Gallego et al. [101]	Al_2O_3/H_2O	40–50 <50 <20	0.13–2.9	– 1.3 1.8	Influence of particle size is very relevant in viscosity enhancement. The classical theories describing viscosity of dilute dispersions could be extended considering aggregation of the nanoparticles
Yu et al. [102]	ZnO/EG	10–20	0.2–5	1.15[a]	Nanofluids with low volume concentrations ($\phi \le 0.02$) exhibit Newtonian behavior while higher volume concentrations ($\phi \ge 0.03$) show non-Newtonian behavior
Tamjid and Guenther [103]	Ag/DEG	40	0.11–4.38	2.04[a]	Particle interactions become more prominent with increasing volume concentration
Yu et al. [55]	Diamond/EG	5–10	1	1.01	Decrease in viscosity of nanofluid with the increase in temperature was attributed to the weakening effect on the inner-particle/intermolecular forces
Pastoriza-Gallego et al. [104]	CuO/H_2O	23–37 11 ± 3	0. 16–1.7	1.14[a] 1.81	Nanofluid with smaller sized nanoparticles shows a significantly larger viscosity due to effects of the electric double layer repulsion
Kole and Dey [20,105]	Al_2O/car coolant CuO/gear oil	<50 40	0.1–1.4 0.5–2.5	2.4 3	Addition of nanoparticles causes non-Newtonian behavior
Abareshi et al. [106]	α-Fe_2O_3-glycerol	5	0.1–0.75	1.37	Nanofluid exhibited non-Newtonian behavior at lower temperatures
Timofeeva et al. [109]	SiC/H_2O $SiC/EG + H_2O$	16, 29, 66 and 90	4	1.8[b] 1.55[b]	Viscosity increase should be independent of the viscosity of the base fluid and only proportional to the particle volume concentration

[a] Calculated from the viscosity data.
[b] For 6 nm.

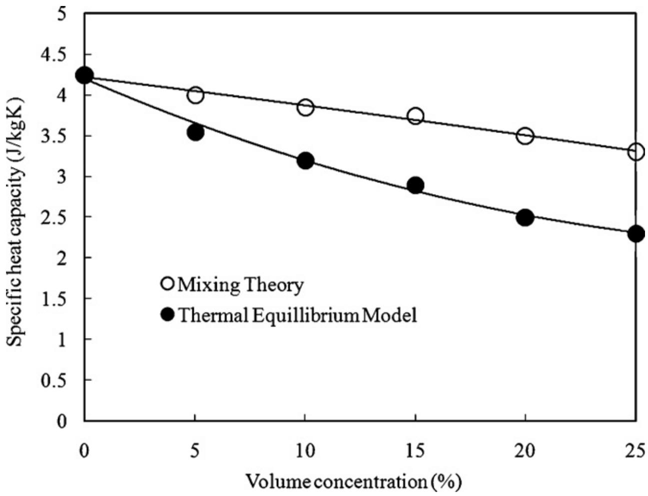

Fig. 2. Deviation between the values of specific heat of water-based Al_2O_3 nanofluid calculated by mixing theory and thermal equilibrium model [117].

2.5. Surface tension

As surface tension is known to be an important parameter in boiling, it was measured for the Al_2O_3/H_2O fluid using the conventional ring method by Das et al. [119]. They observed that the variation of surface tension with particle volume concentration which is extremely nominal to have any surfactant effect on the boiling process.

Prakash Narayan et al. [120] have explained that the surface tension will definitely have a significant influence on boiling process due to its dependency of bubble departure and equilibrium conditions at the interfacial. At room temperature, surface tension does not show a significant change. Logically, the existence of active particles at the liquid–vapor interface is likely to have an influence on the value of the effective surface tension at near saturation temperatures when phase change is in inception. However, it is difficult to believe that this effect alone can bring about such a large amount of influence on the boiling process. Moreover, whatever is the effect of surface tension, it is not likely to be reversed for different cases of the same fluid and hence cannot explain the anomalous behavior of enhancement of boiling in one range and deterioration in another range. Hence it is mentioned that further comprehensive investigations are needed to understand the effect of surface tension on boiling heat transfer.

Shi et al. [121] conducted experiments with iron (Fe) and alumina (Al_2O_3) nanoparticles boiled on a copper block. The authors concluded that Fe particles showed more enhancement than Al_2O_3 particles and that enhancement was mostly due to increases in thermal conductivity and lowered surface tension.

Kumar and Milanova [122] demonstrated that single-walled carbon nanotube (CNT) suspensions in a boiling environment can extend the saturated boiling regime and postpone catastrophic failure of the material if the surface tension of the nanofluid is carefully controlled. Hence they concluded that the heat transfer behavior is dictated not only by the deposition of nanotubes on the heated wire but also by the surface tension, which is a precursor to deposition and postponement of critical heat flux (CHF).

It is demonstrated by Murshed et al. [123] that the burnout heat flux of nanofluid strongly depends nonlinearly on its relaxation of surface tension with base fluid. Similar to the CHF, the burnout heat flux (BHF) of nanofluid also reaches its highest value at NaDBS and CNT concentration ratio of 1:5. The highest BHF value of nanofluid is about 265% enhancement over that for the base fluid at an approximate relaxation surface tension of 25 mN/m. The BHF of deionized water is found to be 1500 kW/m^2. The observed increment of relative BHF of nanofluid (i.e. BHF_N/BHF_W) was attributed to the Marangoni effect which results from the surface tension differences. Thus, the pool boiling heat transfer behavior of surfactant-added nanofluid is not only dictated by the deposition of nanotubes on heater surface, but also by the relaxation of surface tension of nanofluid, which is a precursor to the deposition and overall onsets of both the CHF and BHF.

Zhu et al. [124] measured the surface tension of Al_2O_3/H_2O using the maximum bubble pressure method. With the maximum addition of 1 g/L Al_2O_3 nanoparticles, the surface tension of water increased to a maximum of about 5%. The surface tension of the nanofluids with 0.1 g/L is increased by about 3.4% compared to that of water. Considering the effect of the surface tension, they found that the CHF of nanofluids can be increased by about 1.4% compared to that of water. However, a maximum increase of 120% in CHF for nanofluids compared with that of water was observed in their study and hence they concluded that CHF cannot be related to surface tension of nanofluids, Moosavi et al. [125] prepared ZnO nanofluids by dispersing ZnO nanoparticles in the EG and glycerol as the base fluids. The surface tension ratio of suspensions containing solid particles increased with increasing volume fraction of the solid particles. Since nanofluids are heterogeneous mixtures of nanoparticles dispersed in a base fluid, increasing in surface tension ratio in nanofluids was attributed to the presence of nanoparticles in the surface of base fluid.

The literature survey shows that the experimental works on density of the nanofluid is scant and it could be well predicted using the classical mixing theory. On the other hand, specific heat of nanofluid were calculated using mixing theory and thermal equilibrium model, and it was believed that either one of the theory can be used in predicting the specific heat of nanofluid. Later it was shown that the prediction from the thermal equilibrium model exhibits good agreement while the simple mixing model fails to predict the specific heat of nanofluid. Thus the thermal equilibrium model is used extensively by the researchers to calculate the specific heat of the nanofluid. The property, namely, surface tension becomes pivotal in deciding the heat transfer performance of boiling processes as it offer a situation of variation in surface wettability. As the heat transfer coefficient in boiling heat transfer is inversely proportional to surface tension, a decrease in surface tension with nanofluid compared to base fluid is mandatory to improve boiling heat transfer. The literature search shows that the researchers have reported increase as well as decrease in surface tension of nanofluids and also believe that the variation of surface tension is extremely nominal to bring any significant effect on the boiling process. Under these circumstances, it is learnt that the more experimental research works on surface tension of nanofluids are required to study the effect of variation of surface tension on boiling heat transfer and to create a reliable data base.

3. Forced convective heat transfer

Pak and Cho [110] experimentally investigated the convective heat transfer in the turbulent flow regime using Al_2O_3/water and TiO_2/water nanofluids, and found that the Nusselt number was found to increase with the particle volume concentration and the Reynolds number. Xuan and Li [126] investigated experimentally the convective heat transfer and flow characteristics for Cu/water nanofluid flowing through a straight tube with a constant heat flux under laminar and turbulent flow conditions. The results of the experiment showed that the suspended nanoparticles remarkably enhanced the heat transfer performance of the conventional base fluid and their friction factor data coincided well with that of the water. According to them, the convective heat transfer coefficient

of Cu/water nanofluid is increased about 60% at 2% volume concentration. Both the research groups [110,126] assumed that convective heat transfer enhancement is mainly due to dispersion of the suspended nanoparticles.

Wen and Ding [127] experimentally probed the convective heat transfer of Al_2O_3/water nanofluids in the laminar flow regime and showed that the use of Al_2O_3/water nanofluids can significantly enhance the convective heat transfer in the laminar flow regime, and the enhancement increased with Reynolds number and particle volume concentration. They also showed that (i) the enhancement is significant in the entrance region and decreases with axial distance (ii) the thermal developing length of nanofluids is greater than that of pure base liquid. They attributed the enhancement of the convective heat transfer to particle migration which may result in a non-uniform distribution of thermal conductivity and viscosity field which will reduce the thermal boundary layer thickness. Using the same experimental setup, Ding et al. [77] reported a maximum enhancement in convective heat transfer of over 350% with carbon nanotube (CNT) nanofluids at a Reynolds number of 800 at an axial distance of approximately 110 times the tube diameter. The observed large enhancement of the convective heat transfer was attributed to the enhancement of thermal conductivity, particle re-arrangement, shear induced thermal conduction enhancement, reduction of thermal boundary layer thickness due to the presence of nanoparticles and the very high aspect ratio of CNTs.

The convection heat transfer performance of the graphite nanofluids were studied experimentally by Yang et al. [128] in laminar flow through a circular tube and showed that the nanoparticles increase the heat transfer coefficient of the fluid system in laminar flow, but the increase is much less than that predicted by the correlation based on static thermal conductivity measurements. Hence, they concluded that Reynolds number, temperature, nanoparticle loading, nanoparticle source, and the choice of the base fluid can all affect the heat transfer coefficients of nanofluids.

He et al. [129] carried out experimental study on the flow and heat transfer behavior of aqueous TiO_2 nanofluids flowing through a straight vertical pipe under both laminar and turbulent flow conditions. They observed that for a given Reynolds number and particle size, the convective heat transfer coefficient increased with volume concentration in both the laminar and turbulent flow regimes and was insensitive to the changes in particle size. As the convective heat transfer coefficient, h, can be approximately given by $h = k_f/\delta_t$ with δ_t the thickness of thermal boundary layer, they attributed that both an increase in k_f and a decrease in δ_t increased the convective heat transfer coefficient of nanofluid. Their measured pressure drop of nanofluids was very close to that of the base liquid for a given Reynolds number.

Chen et al. [80] with titanate nanotubes (TNT) nanofluids concluded that, compared with thermal conduction, the enhancement of the convective heat transfer was much higher and the enhancement depends on nanotube concentration, Reynolds number and the axial position. Given the nanotube concentration and Reynolds number, the highest enhancement was observed at the entrance region; the enhancement decreased with increasing axial distance and approached a constant value in the fully developed region. Nanoparticle shape is shown to have a significant effect on the observed enhancement of the convective heat transfer coefficient, which was consistent with the reported results of nanofluids containing carbon nanotube nanofluids (aspect ratio ~ 100), spherical nanoparticles (aspect ratio = 1) and disc-like nanoparticles (aspect ratio ~ 0.02). They suggested that the possible mechanisms of convective heat transfer coefficient enhancement include enhanced conduction under both static and dynamic conditions, particle re-arrangement under shear, enhanced wettability, particle shape effect and aggregation (structuring).

Duangthongsuk and Wongwises [130] have presented for the first time the heat transfer and flow characteristics of nanofluid consisting of water and TiO_2 nanoparticles at 0.2% volume concentration in a double-tube heat exchanger. The results showed that the convective heat transfer coefficient of nanofluid was only slightly higher than that of the base liquid by about 6–11% and has a little penalty in pressure drop. The reasons for this enhancement were attributed with (i) the nanofluid with suspended nanoparticles increases the thermal conductivity of the mixture and (ii) a large energy exchange process resulting from the chaotic movement of nanoparticles. The same research group [131] with same experimental setup and nanofluid studied the effect of various thermophysical property models on predicting the forced convective heat transfer performance of nanofluid. They reported that the various thermophysical models have no significant effect on the predicted values of the heat transfer coefficient of the nanofluid. They also concluded that the reliability and accuracy of the experimental heat transfer coefficient may depend on the experimental system calibration rather than the models for thermophysical properties of nanofluid.

Anoop et al. [132] conducted convective heat transfer experiments using Al_2O_3/water nanofluids in the developing region of pipe flow with constant heat flux to evaluate the effect of particle size on convective heat transfer coefficient. In their work, two particle sizes (45 nm and 150 nm) were used and it was observed that the nanofluid with 45 nm particles showed higher heat transfer coefficient than that with 150 nm particles. They concluded that the observed increase in convective heat transfer with nanofluids is due to some effects beyond the increase in thermal conductivity like particle migration effects and thermal dispersion.

Heris et al. [133] reported laminar flow forced convection heat transfer of Al_2O_3/water nanofluid inside a circular tube with constant wall temperature. They concluded that thermal conductivity increase is not the sole reason for heat transfer enhancement in nanofluids. Other factors such as dispersion and chaotic movement of nanoparticles, Brownian motion, particle migration, particle fluctuations and interactions, especially in high Peclet number may cause changes in flow structure and lead to augment heat transfer due to the presence of nanoparticles.

Hwang et al. [134] measured the pressure drop and convective heat transfer coefficient of water-based Al_2O_3 nanofluids flowing through a uniformly heated circular tube in the fully developed laminar flow regime. The experimental results showed that the convective heat transfer coefficient enhancement exceeds, by a large margin, the thermal conductivity enhancement. Therefore, they discussed the effects of thermal conductivities under static and dynamic conditions, energy transfer by nanoparticle dispersion, nanoparticle migration due to viscosity gradient, non-uniform shear rate, Brownian diffusion and thermophoresis on the remarkable enhancement of the convective heat transfer coefficient of nanofluids. Based on scale analysis and numerical solutions, it was shown that the flattened velocity profile due to particle migration induced by Brownian diffusion and thermophoresis is a possible mechanism of the convective heat transfer enhancement, which cannot be explained by an increase in the thermal conductivity of nanofluids alone.

The heat transfer rates were measured by Yu et al. [135] in the turbulent flow of SiC/water nanofluid consisting of a volume concentration of 3.7% with 170 nm silicon carbide particles. Heat transfer coefficient increase of 50–60% above the base fluid water was obtained when compared on the basis of constant Reynolds number. Heat transfer mechanisms that involve particle interactions are believed for heat transfer enhancement.

The thermal–hydraulic performances of dilute suspensions of 10 nm aluminum oxide nanoparticles in propanol was explored by Sommers and Yerkes [111] recently. Their results revealed

that the observed augmentation in heat transfer was the result of the enhanced thermophysical properties of the Al_2O_3/propanol nanofluid and not due to mechanisms like Brownian motion-induced nanoconvection, liquid layering, or other interfacial effects. Two different mechanisms have been proposed to explain this enhancement. First, it is believed that the addition of the nanoparticles may have actually served to precipitate an earlier transition from laminar to turbulent flow which would mean higher Nusselt numbers. A second mechanism which might explain enhancement lies with the rheology of the fluid. Because the nanofluid is shear thinning and the shear rate is highest near the wall, better fluid flow performance should be realized near the wall. Thus, the non-uniform distribution of the viscosity field across the tube cross-section (and/or the possibility of a reduced boundary layer) might also explain this enhancement.

Turbulent convective heat transfer performance and pressure drop of very dilute (less than 0.24% volume) CuO/water nanofluid flowing through a circular tube were investigated experimentally by Fotukian and Esfahany [136]. The increase in heat transfer coefficient was observed to be on an average of 25% with 20% penalty in pressure drop. The augmentation of heat transfer coefficient was not attributed to the increase of thermal conductivity but due to the augmented thermal energy transfer from the wall to the nanofluid flowing in the tube in the presence of nanoparticles. It is proposed that the nanoparticles hit the wall and absorb thermal energy, lowering the wall temperature and mix back with the bulk of the fluid resulting in enhanced thermal performance. The same research group [137] has also investigated the turbulent flow convective heat transfer performance and pressure drop of dilute Al_2O_3/water nanofluids inside a circular tube. The increase in heat transfer coefficient was observed to be on an average of 45% with 30% penalty in pressure drop. They have reported the same mechanism for enhanced thermal performance of dilute Al_2O_3/water nanofluid as reported in their other work [136] with dilute CuO/water nanofluid.

Williams et al. [138] have published an interesting finding that the convective heat transfer and pressure loss behavior of the alumina/water and zirconia/water nanofluids tested in fully developed turbulent flow can be predicted by means of the traditional correlations and models, as long as the effective nanofluid properties are used in calculating the dimensionless numbers. They have also stated that there is no abnormal heat transfer enhancement with nanofluids. Similar results were reported by Rea et al. [139] under laminar flow with alumina–water and zirconia–water nanofluids. They suggested that the nanofluids behave as homogeneous mixtures and the heat transfer coefficient enhancement is not abnormal, but simply due to the different mixture properties of the nanofluids.

Buongiorno [116] theoretically probed the abnormal convective heat transfer enhancement observed in nanofluids and concluded that energy transfer by nanoparticle dispersion and turbulence, which is commonly stated in the literature, is negligible. He proposed that the properties may vary significantly within the boundary layer because of the effect of the temperature gradient and thermophoresis. However, the above mechanisms are proposed to explain the convective heat transfer of nanofluid in turbulent regime.

The literature review on forced convective heat transfer of nanofluids has also revealed that the evaluation of heat transfer characteristics at a constant Reynolds number value may bring out misleading results. This is evident from the results of Pak and Cho [110] who found, under the condition of constant average velocity, the convective heat transfer coefficient of the dispersed fluid to be 12% smaller than that of pure water. Similarly Yu et al. [135] showed that, at a constant velocity, the heat transfer coefficient of the SiC/water nanofluid is 7% below that of the base fluid. This trend of lower heat transfer coefficients in nanofluids under constant velocity also occurred in aluminum oxide/water, titanium oxide/water, and zirconium oxide/water nanofluids [138,139]. The reasons for this result are complex and were attributed to the combination of thermal conductivity enhancement and viscosity increase found in the nanofluids. Enhanced thermal conductivity reduces resistance to thermal diffusion in the laminar sublayer of the boundary layer. However, increased viscosity increases the thickness of the sublayer and in turn increases its resistance to heat transfer. The net heat transfer enhancement effect depends on the magnitudes of these competing phenomena.

There are 13 heat transfer enhancement techniques that can be segregated into active and passive techniques. Passive techniques employ insert devices or fluid additives [140]. Insert devices are geometrical modification and nanofluids are fluids containing nanosized additives. Both belong to the passive technique of heat transfer enhancement and hence, there is a basis for possible comparison of thermo–hydraulic behavior of these two techniques. Based on this, experimental investigations on the thermo–hydraulic performance of nanofluids in combination with twisted tape, wire coil inserts, longitudinal strip insert and dimpled tube were also reported.

Sharma et al. [141] conducted experiments to evaluate heat transfer coefficient and friction factor characteristics of Al_2O_3/water nanofluid flowing in a tube with twisted tape inserts under transition range of flow. Their results also showed considerable enhancement of convective heat transfer with Al_2O_3 nanofluids compared to water which was attributed to higher values of nanofluid thermal conductivity and viscosity reflected in the index of Prandtl number. They demonstrated that the inclusion of twisted tape in the flow path gives higher heat transfer rates compared to flow in a plain tube for nanofluid as well as water. Using the same experimental setup, Sundar and Sharma [142] evaluated heat transfer coefficient and friction factor characteristics of Al_2O_3/water nanofluid flowing in a tube with twisted tape inserts under turbulent flow also.

Sundar and Sharma [143] also performed experimental investigations to determine the heat transfer enhancements of low volume concentration Al_2O_3 nanofluid combined with longitudinal strip inserts in a circular tube. It was demonstrated that heat transfer coefficients obtained are higher with longitudinal strip inserts compared to values observed with the flow of nanofluid.

Convective heat transfer and friction factor characteristics of Al_2O_3/water nanofluid flowing through a uniformly heated horizontal tube with and without wire coil inserts under laminar flow were presented in our previous work [144]. The better heat transfer performance of nanofluid with wire coil insert is attributed to the effects of dispersion or back-mixing which flattens the temperature distribution and make the temperature gradient between the fluid and wall steeper.

An experimental investigation on the convective heat transfer and friction factor characteristics of CuO/water nanofluid in plain and helically dimpled tube under laminar and turbulent flow with constant heat flux was also reported recently [145,146]. Dimpled tube is chosen because the dimples formed on the surface of tube will create vortices in the fluid flow near the wall that would disturb the boundary layer and hence could provide some experimental evidence for the mechanism of convective heat transfer enhancement in nanofluids. The use of dimpled tube resulted in further increase in Nusselt numbers at all Reynolds numbers in turbulent regime and the reason for enhancement is attributed as disturbance caused to the laminar sublayer due to the presence of the dimples.

Comparison of thermal performance of helical screw tape inserts with Al_2O_3/water and CuO/water nanofluids through a straight circular duct with constant heat flux boundary condition under laminar and transition flow were also reported [147,148]. Thermal performance factor of helical screw tape inserts using

CuO/water nanofluid is found to be higher when compared with the corresponding value using Al_2O_3/water. The higher enhancement shown by CuO/water nanofluid compared to Al_2O_3/water nanofluid was due to the combined effect of greater surface area to volume ratio and thermal conductivity of CuO nanoparticles compared to Al_2O_3 particles.

Wongcharee and Eiamsa-ard [149] experimentally investigated the heat transfer, friction and thermal performance characteristics of CuO/water nanofluids in a circular tube equipped with the modified twisted tape with alternate axis (TA) and the typical twisted tape (TT) in the laminar regime. They demonstrated that the simultaneous use of nanofluid and TA improves Nusselt number up to 13.8 times of the plain tube. Over the range investigated, the maximum thermal performance factor of 5.53 is found with the simultaneous employment of the CuO/water nanofluid at 0.7% volume and the TA at Reynolds number of 1990. Enhancement of heat transfer performance is explained by the fact that the TA gives superior efficient fluid mixing induced by the altering flow pattern while the TT causes swirl flow only and hence it is attributed to the combined effect of both enhancing techniques.

The same research group [150] has also presented the investigations on the heat transfer enhancement by using CuO/water nanofluid in a corrugated tube fitted with twisted tape. It was demonstrated that at similar operating conditions, heat transfer rate and friction factor associated with the simultaneous application of CuO/water nanofluid and twisted tape are higher than those associated with the individual techniques. In addition, the twisted tape coupled with corrugated tube in counter pattern offer higher heat transfer performances than the ones in parallel pattern. This can be the consequence of the combined mechanisms induced by all used techniques.

Saeedinia et al. [151] indicated clearly with their experimental results that for a specific nanoparticle concentration, the increase in both heat transfer and pressure drop is obtained by inserting coil wires. It was also demonstrated that at nearly the same range of Reynolds numbers, the effect of increasing the diameter of wire is more prominent than the effect of decreasing the coil pitch on heat transfer enhancement. The reason responsible for this behavior can be the increased level of flow turbulence made by separation and reattachment mechanism using wire coils. Besides, whenever wire coil is in contact with the tube wall, it acts as a turbulence promoter and increases the disturbances of nanoparticles in the laminar sublayer region.

To understand the enhancements in the heat transfer rates and the wall friction, experimental investigations on convective heat transfer and pressure drop characteristics of Al_2O_3/water nanofluid was carried out in the fully developed turbulent region of pipe flow with constant heat flux with spiraled rod inserts by Suresh et al. [152]. It was observed that the Nusselt number for spiraled rod inserts with nanofluid increased by about 10–48% compared to the Nusselt numbers obtained with plain tube and the isothermal pressure drop for turbulent flow with spiraled rod inserts were found to be between 2% and 8% higher than the plain tube.

It is striking to note the research works [141–143] have not differentiated between the mechanisms involved in the heat transfer enhancement obtained with the use of nanofluid and combination of nanofluid with tape inserts whereas the differentiation in mechanisms were provided in the research works [144–152].

As the reduction in boundary layer thickness by mixing effects of particles near the wall is expected to be one of the reasons of enhanced heat transfer performance of nanofluids, the use of wire coil inserts or dimpled tube could be a better choice compared to twisted tape, longitudinal strip or spiraled rod inserts. This is because the wire coil inserts or dimpled tube mainly disturbs the flow near the wall while the twisted tape or longitudinal tape inserts disturb the entire flow field. In addition, wire coil inserts and dimpled tube have the advantages of lesser pressure drop, low cost, easy installation and removal [153].

From the above literature review on forced convective heat transfer, it is understood that the previous works has suggested a list of mechanisms for enhanced heat transfer with nanofluids. The summary of some important published experimental investigations of the convective heat transfer performance of various nanofluids and the mechanisms proposed by the various researchers is given in Table 5. A brief summary of the research works on heat transfer behavior of nanofluids when used in conjunction with modified tube geometry is given in Table 6. In the bulk of the literature reviewed, the mechanism for enhanced heat transfer with nanofluids is by and large attributed to thermal dispersion and intensified turbulence, brought about by nanoparticle motion. It is also clear that the experimental investigations which provide experimental evidence for the mechanisms proposed were not sufficient and hence there is scope for further probing with respect to the mechanisms of convective heat transfer enhancement in future research works.

4. Concluding remarks and directions for future work

A review on the mechanisms proposed for alteration of thermophysical properties and forced convective heat transfer characteristics of various nanofluids based on experimental results were presented in this article. Based on the literature reviewed, it is clear that the exact mechanism for alteration of thermophysical properties and forced convective heat transfer characteristics is still unclear. The mechanisms proposed lie in a diverse spectrum as summarized in Tables 3–6.

The convective heat transfer coefficient (h) for convective/boiling heat transfer can be generally expressed as function of thermophysical properties of fluid and is given by

$$h = \frac{k^a \rho^b c_p^c}{\mu^d \sigma^e} \tag{4}$$

where a, b, c, d, e are empirical or theoretical constants that depend on different boundary and geometrical conditions, and the constant e is normally zero for convections without phase change [35]. The addition of nanoparticles into a base liquid could affect all these properties thus affecting the heat transfer coefficient. Eq. (4) indicates that heat transfer coefficient (h) must increase with increases in thermal conductivity (k), density (ρ) and specific heat (c_p) while it must increases with decreases in viscosity (μ) and surface tension (σ). The review of nanofluid literature indicates (i) increase in thermal conductivity (ii) increase in density (iii) decrease in specific heat (iv) increase in viscosity and (v) increase as well as decrease in surface tension. Hence it is observed that properties like thermal conductivity and density will have positive influence while the other properties have a negative effect on the heat transfer coefficient. This emphasis that the best combination of nanoparticle and base fluid must be selected to have optimized nanofluid thermophysical properties to make nanofluids beneficial as coolants in flow based cooling. Hence the need for optimization of nanofluid properties shows some new direction for future research.

The review on the thermal conductivity of nanofluids reveals that a long list of physical reasons or phenomenon has been proposed to explain the experimentally observed increase in thermal conductivity of nanofluids. The experimental works on thermal conductivity of nanofluid provides support for the affirmations like

- Smaller sized nanoparticles could bring Brownian motion at higher temperatures.
- The microstructure of the nanofluid could provide details regarding the alignment of the nanoparticles or the cluster formation.

Table 5
Summary of forced convection experimental studies on nanofluids.

Researcher	Nanofluid	Flow regime	Boundary condition	Mechanism of heat transfer enhancement
Pak and Cho [110]	Al_2O_3/water	Turbulent	Constant heat flux	Dispersion of the suspended nanoparticles
Xuan and Li [126]	Cu/water	Laminar and turbulent	Constant heat flux	Dispersion of the suspended nanoparticles
Wen and Ding [127]	Al_2O_3/water	Laminar flow/entrance region	Constant heat flux	Particle migration resulting in a non-uniform distribution of thermal conductivity and viscosity field reducing the thermal boundary layer thickness
Ding et al. [77]	CNT/water	Laminar flow/entrance region	Constant heat flux	Enhancement of thermal conductivity, particle re-arrangement, shear induced thermal conduction enhancement, reduction of thermal boundary layer thickness due to the presence of nanoparticles
Yang et al. [128]	Graphite/oil	Laminar	Double pipe heat exchanger	Reynolds number, temperature, nanoparticle loading, nanoparticle source, and the choice of the base fluid can all affect the heat transfer coefficients of nanofluids
He et al. [129]	TiO_2/water	Laminar and turbulent	Constant heat flux	The convective heat transfer coefficient, h, can be approximately given by $h = k_f/\delta_t$ with δ_t the thickness of thermal boundary layer, hence both an increase in k_f and a decrease in δ_t increased the convective heat transfer coefficient of nanofluid
Chen et al. [80]	TNT/water	Laminar	Constant heat flux	Enhanced conduction under both static and dynamic conditions, particle re-arrangement under shear, enhanced wettability, particle shape effect and aggregation (structuring)
Duangthongsuk and Wongwises [130,131]	TiO_2/water	Turbulent	Double pipe heat exchanger	Suspended nanoparticles increases the thermal conductivity of the mixture and a large energy exchange process resulting from the chaotic movement of nanoparticles Accuracy of the experimental heat transfer coefficient may depend on the experimental system calibration rather than the models for thermophysical properties of nanofluid
Anoop et al. [132]	Al_2O_3/water	Laminar/developing flow	Constant heat flux	Particle migration effects and/or thermal dispersion
Heris et al. [133]	Al_2O_3/water	Laminar/developing flow	Constant wall temperature	Dispersion and chaotic movement of nanoparticles, Brownian motion, particle migration, particle fluctuations and interactions, cause changes in flow structure and lead to augment heat transfer
Hwang et al. [134]	Al_2O_3/water	Laminar/developed flow	Constant heat flux	Flattened velocity profile due to particle migration induced by Brownian diffusion and thermophoresis is the possible mechanism of the convective heat transfer enhancement
Yu et al. [135]	SiC/water	Turbulent	Constant heat flux	Heat transfer mechanisms that involve particle interactions
Sommers and Yerkes [111]	Al_2O_3/propanol	Laminar and turbulent	Counter flow heat exchanger	Earlier transition from laminar to turbulent due to the presence of nanoparticles. Non-uniform distribution of the viscosity field across the tube cross-section (and/or the possibility of a reduced boundary layer) might explain this enhancement
Fotukian and Esfahany [136,137]	Al_2O_3/water	Turbulent	Constant wall temperature	Augmented thermal energy transfer from the wall to the nanofluid flowing in CuO/water the tube in the presence of nanoparticles
Williams et al. [138] and Rea et al. [139]	Al_2O_3/water	Turbulent	Constant heat flux	Heat transfer coefficient enhancement is not abnormal, but due to the different mixture properties

- Measurement of pH together with zeta potential could provide the information regarding stability of the prepared nanofluid.
- Application of magnetic field to control the structure of magnetic nanoparticles suspended in the magnetic fluids.

At the same time, it must be noted that there is no sufficient experimental technique to prove the presence of nanolayer and the value of its thickness. As the answer to the question “Which is the dominant heat transport mechanism responsible for thermal conductivity enhancement in nanofluids?” remains open, it seems it is the right time for the scientific community to develop experimental techniques to verify and decide the dominant heat transport mechanism in nanofluids.

The assessment of literature on the viscosity of the nanofluid shows that

- Viscosity may increase linearly or nonlinearly with volume concentration.
- Viscosity of nanofluid decreases with the increase in temperature.
- Viscosity of nanofluid increases with the decrease in particle size.
- Nanofluid may exhibit Newtonian or non-Newtonian behaviors which were coupled with the level of volume concentration.

Table 6
Summary of the research works on heat transfer behavior of nanofluids in conjunction with modified tube geometry.

Researcher	Nanofluid	Type of geometry	Flow regime	Mechanism of heat transfer enhancement with	
				Nanofluid	Nanofluid + geometry type
Sharma et al. [141]	Al_2O_3/water	Twisted tape insert	Transient	Increased thermal conductivity and viscosity resulted in high Prandtl number	Not mentioned
Sundar and Sharma [142]	Al_2O_3/water	Twisted tape insert	Turbulent	Increased thermal conductivity and viscosity resulted in high Prandtl number	Not mentioned
Sundar and Sharma [143]	Al_2O_3/water	Longitudinal tape insert	Turbulent	Increased thermal conductivity and viscosity resulted in high Prandtl number	Not mentioned
Chandrasekar et al. [144]	Al_2O_3/water	Wire coil insert	Laminar	List of probable mechanisms proposed by previous researchers	Irregular and random movement of the particles which increases the energy exchange rates in the fluid
Suresh et al. [145,146]	CuO/water	Dimpled tube	Laminar and turbulent	List of probable mechanisms proposed by previous researchers	Increased disturbance in the laminar sublayer of the boundary layer due to the presence of the dimples
Suresh et al. [147,148]	Al_2O_3/water CuO/water	Helical screw tape inserts	Laminar and transition	List of probable mechanisms proposed by previous researchers	Higher turbulence intensity of the fluid close to the tube wall is responsible for an excellent fluid mixing and an efficient redevelopment of the thermal/hydrodynamic boundary layer
Wongcharee and Eiamsa-ard [149]	CuO/water	Twisted tape with alternate axis	Laminar	Increased thermal conductivity and collision of nanoparticles which are favorite factors for heat transfer enhancement	Superior efficient fluid mixing induced by the altering flow pattern
Wongcharee and Eiamsa-ard [150]	CuO/water	Corrugated tube equipped with twisted tape	Turbulent	Same as indicated ref [149]	Corrugated tube and twisted tape possibly promotes the dispersion and random movement of the particles with large contact surfaces between fluid and wall
Saeedinia et al. [151]	CuO/Engine oil	Wire coil insert	Laminar flow	Due to thermal conductivity enhancement	Wire coils act as a turbulence promoter and increase the disturbances of nanoparticles in the laminar sublayer region
Suresh et al. [152]	Al_2O_3/water	Spiraled rod inserts	Turbulent	Same as indicated in ref. [145–148]	The pins act as triggers and promoters of turbulence Secondary flow develops as the flow field is spiraled inside the annulus Spiraled rod reduces the hydraulic diameter of the heat exchanger

- Possible mechanisms for alteration in viscosity of nanofluid include hydrodynamic interactions between particles, increased surface of particles, increase of energy dissipation rate, combined effects of electroviscous forces and particle aggregation and effects of the electric double layer repulsion.

The fact i.e., decrease in viscosity with increase in temperature is promising for using nanofluids as enhanced coolants in thermal management systems. However, the phenomenon of hysteresis reported by Nguyen et al. [98] is to be considered to ensure reliable and successful application of nanofluid in heat transfer systems and requires further investigation. The findings of Wang et al. [108] about the decrease of thermal conductivity with increase in viscosity of nanofluid and the limiting viscosity value to decide whether the Brownian motion is active or inactive has also created new direction for future research works.

The literature survey shows that the experimental works on density and specific heat of the nanofluid is limited. It is learnt that

- Density of nanofluid could be well predicted using the classical mixing theory.
- Specific heat of nanofluids was calculated using two models, namely, mixing theory and thermal equilibrium model. Through experiment it was demonstrated that the prediction from the thermal equilibrium model exhibits good agreement while the simple mixing model fails to predict the specific heat of nanofluid.

Hence, the mixing model and the thermal equilibrium model are used extensively by the researchers to calculate the density and specific heat of the nanofluid respectively. More experimental works on the measurement of density and specific heat will be very helpful for the nanofluid research.

Surface tension of the fluid becomes pivotal in deciding the heat transfer performance of boiling processes as it has an impact on surface wettability. The literature search shows that the researchers have reported increase as well as decrease in surface tension of nanofluids and also believe that the variation of surface tension is extremely nominal to bring any significant effect on the boiling process. Under these circumstances, it is learnt that more experimental research works on surface tension of nanofluids are required to have a reliable data base to study the effect of variation of surface tension on boiling heat transfer.

The experimental investigations on the convective heat transfer performance of various nanofluids indicates that the key mechanisms may include

- Dispersion of the suspended nanoparticles.
- Particle migration resulting in a non-uniform distribution of thermal conductivity and viscosity in the flow field.
- Reduction of thermal boundary layer thickness.
- Enhanced conduction under both static and dynamic conditions.
- Particle shape effect and aggregation (structuring).

- Enhanced energy exchange process resulting from the chaotic movement of nanoparticles.
- Flattened velocity profile due to particle migration induced by Brownian diffusion.
- Thermophoresis.
- Earlier transition from laminar to turbulent due to the presence of nanoparticles.
- Augmented thermal energy transfer from the wall to the nanofluid.

It is worth mentioning the work of Walsh et al. [154] who described a novel application of micro-particle image velocimetry in attaining measurements within nanofluids and demonstrated how these can be used in developing theories based on observed flow or to validate/negate many of the recently proposed theories attempting to elucidate the mechanisms at play in nanofluids. Hence, future research requires a thorough investigation on the impact of the various mechanisms proposed and there is an urgent need to device experimental methods to verify these affirmations. It is also clear that it will be essential to consider not only one possible mechanism but to combine several mechanisms while explaining and benchmarking the observed experimental data sets.

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